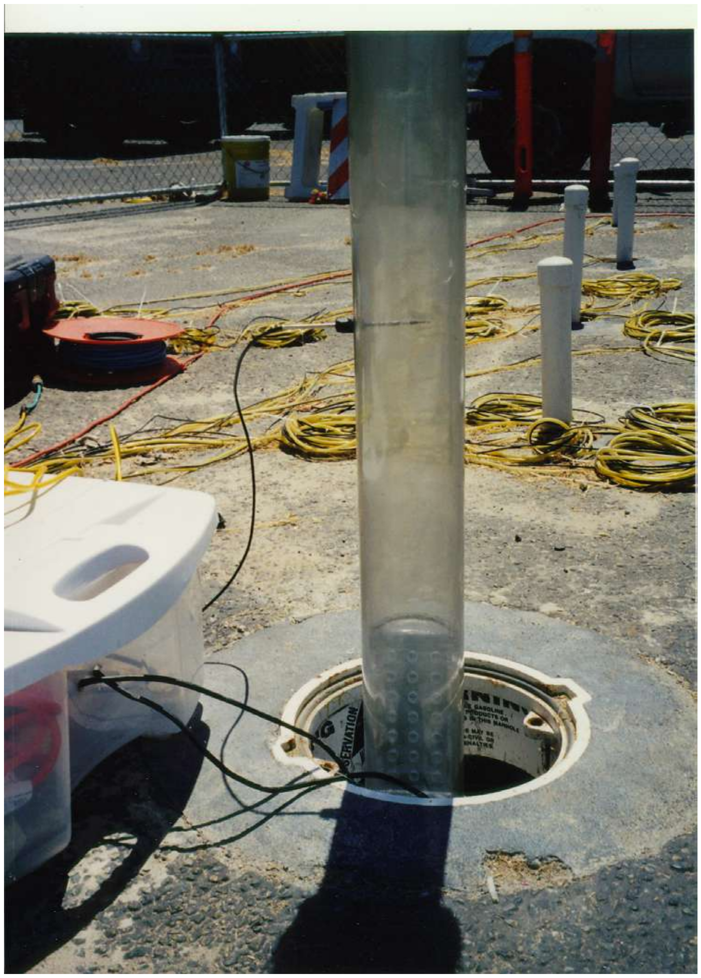
Design Document
For
Passive Bioventing



March 2006

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **MAR 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**
4. TITLE AND SUBTITLE **Design Document for Passive Bioventing**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Facilities Engineering Service Center,1322 Patterson Ave. SE, Suite 100,Washington Navy Yard,DC,20374-5065**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**62**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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TO: Director, Freedom of Information & Security Review, Rm. 2C757, Pentagon

1. DOCUMENT DESCRIPTION	
a. TYPE Technical Report	b. TITLE Design Document for Passive Bioventing (ER-9715)
c. PAGE COUNT 61	d. SUBJECT AREA Environmental Security Technology Certification Program (ESTCP)

2. AUTHOR/SPEAKER		
a. NAME *(Last, First, Middle Initial)* Larson, Sherrie	b. RANK	c. TITLE
d. OFFICE Naval Facilities Engineering Service Center		e. AGENCY U.S. Navy

3. PRESENTATION/PUBLICATION DATA *(Date, Place, Event)*

OPTIONAL FORM 99 (7-90)

Posting on the ESTCP web site.

NSN 7540-01-317-7368 5099-101 GENERAL SERVICES ADMINISTRATION

4. POINT OF CONTACT	
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6. REMARKS

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e. OFFICE OUSD(I&E)	f. AGENCY OUSD (A&T)
g. SIGNATURE	h. DATE SIGNED *(YYYYMMDD)* 20060627

DD FORM 1910, MAR 1998 (EG) PREVIOUS EDITION MAY BE USED. WHS/DIOR, Mar 98

06-S-1980

ESTCP Project : ER-9715

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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
AFS	Air Force Station
bgs	below ground surface
cfd	cubic feet per day
cfm	cubic feet per minute
DoD	Department of Defense
ESTCP	Environmental Security Technology Certification Program
ft	feet
GMS	Groundwater Modeling System
LBNL	Lawrence Berkeley National Laboratory
mbar	millibar
NRC	National Research Council
NSY	Naval Shipyard
OD	outside diameter
Pa	
psi	pounds per square inch
RCRA	Resource Conservation and Recovery Act
SAIC	
SSE	sum of squared error
SVE	soil vapor extraction
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USEPA	United States Environmental Protection Agency
USEPA ORD	USEPA Office of Research and Development
VMPs	vapor monitoring points

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1.0 EXECUTIVE SUMMARY

Bioventing is a process of aerating water-unsaturated soils to stimulate in situ biologic activity and promote the bioremediation of nonchlorinated hydrocarbons. Conventional bioventing systems use at least one electrically powered blower to inject air, thereby aerating the hydrocarbon contaminated subsurface. Passive bioventing utilizes the difference between atmospheric and subsurface gas pressures, which develop with changes in barometric pressure, to drive air through vent wells for aerating contaminated soils. This document provides the information necessary to identify sites where barometric pressure changes are anticipated to induce airflow in vent wells, design and install a pilot-test system for evaluating the feasibility of using passive bioventing, and design a full-scale passive bioventing system.

Passive bioventing may be an alternative approach to conventional bioventing at Department of Defense (DoD) sites where electrical power is either unavailable or would be expensive to obtain such as training and proving grounds, and ranges. Even at facilities where electrical power is available, contaminated sites are often not conveniently located near power distribution points. At these locations, passive bioventing may be a cost-effective approach. At sites being treated with conventional bioventing systems where contaminant concentrations are no longer decreasing, switching to a passive bioventing approach might be appropriate since the rate of biotransformation is limited by the low hydrocarbon concentration rather than the rate of oxygen delivery.

Specific subsurface lithologic and stratigraphic conditions must exist for any change in barometric pressure to induce significant airflow through vent wells. A thick (e.g., >100 ft) soil layer of high air permeability or a thin soil layer of low air permeability can retard the flow of air between the atmosphere and subsurface, leading to a gas pressure difference. While the magnitude of this naturally occurring pressure difference is low, between about 0.06 in to 0.5 in of water (15 to 125 Pa), the rate of barometric pressure-driven airflow through vent wells can range from 0.5 cu ft to more than 50 cu ft per minute.

Passive bioventing has been successfully demonstrated at four sites where the depth to groundwater is greater than 100 ft. A search for shallow groundwater sites where passive bioventing could be successfully applied was conducted at 15 DoD sites throughout the contiguous United States. These sites were identified as having favorable lithologic and stratigraphic conditions, and passive bioventing was found to be feasible at three of the 15 sites based on short-term airflow measurements.

This document contains four sections. Section 2 provides a brief introduction to passive bioventing and summarizes previous demonstration results. Section 3 describes procedures used to determine the suitability of a site for passive bioventing. Section 4 describes the materials and methods used to demonstrate the feasibility of passive bioventing. Section 5 details design considerations for a full-scale passive bioventing system.

Section 3 contains procedures for estimating the rate of airflow based on the soil types located between the ground surface and hydrocarbon contaminated soil (i.e., lithology or stratigraphy). A series of charts can be used to estimate soil air-permeability based on soil type, differential

pressure based on soil air-permeability, and daily barometric pressure change based on historical averages for the contiguous United States. The values from these charts can then be used to predict the rate of airflow using a mathematical model developed for passive soil venting. A summary of the subsurface conditions that, if present, would justify a pilot test (go decision) or, if not present, would make the site an unlikely candidate for passive bioventing (no-go decision) is also provided.

Section 4 covers the key parameters that have to be measured during a pilot test to design and estimate the cost of a full-scale passive bioventing system. Included are details on the construction and layout of vent wells and vapor monitoring points, types of one-way passive valves, along with instruments used to measure airflow rate, differential pressure, and subsurface oxygen concentration. Also included are procedures used for analyzing pilot test data to determine the oxygen utilization rate and the radius of oxygen influence and to calibrate a mathematical model that was developed to predict the rate of airflow using only differential pressure.

Section 5 provides details supplemental to the existing bioventing design manuals and books regarding the design of passive bioventing systems, including vent well spacing and layout, and performance monitoring.

2.0 INTRODUCTION

Petroleum hydrocarbons can be removed from soil using a variety of remediation technologies, including excavation of contaminated soil with off-site disposal (i.e., dig and haul) and vacuum extraction to recover volatile hydrocarbons (i.e., soil vapor extraction). Bioventing is an alternative remediation method that involves pumping air into water-unsaturated soils to stimulate in-situ aerobic biologic activity. Microbes then transform petroleum hydrocarbons into biomass and carbon dioxide, thereby transforming the unwanted contaminants into benign products.

Passive bioventing, the subject of this document, uses the difference between subsurface and atmospheric gas pressure to deliver air into contaminated soils and thus eliminates the need for the electrically powered blower normally used in conventional bioventing. However, removing the electrical blower and relying on the relatively small pressure difference that arises between the subsurface and atmosphere does reduce airflow rates and the total volume of air delivered into the contaminated subsurface region. Also, passive bioventing will work only at sites with suitable subsurface conditions that lead to sustained differences between atmospheric and subsurface gas pressure. Despite these limitations, passive bioventing may hold a cost advantage over conventional bioventing while achieving the same rate of hydrocarbon remediation. For example, electrical power is either unavailable or would be expensive to obtain at many Department of Defense (DoD) facilities such as ranges, and training and proving grounds. Even at facilities where electrical power is available, contaminated sites are often not conveniently located near power distribution points, resulting in an increase in installation costs. At these locations, passive bioventing may be a cost-effective approach. Another situation where passive bioventing may be applicable is at sites with active conventional bioventing systems where contaminant concentrations have stabilized and are no longer decreasing. The cost of operating an electrical blower at these sites may no longer be justified as the rate of biotransformation is limited by the low hydrocarbon concentration rather than the rate of oxygen delivery. Thus, the lower airflow rate provided by passive bioventing may be appropriate to treat the petroleum contamination that remains after the bulk has been remediated using conventional bioventing or soil vapor extraction.

The overall goal of this document is to provide guidelines on selecting locations where a difference between subsurface and atmospheric gas pressure is expected to occur and cause air to flow into the subsurface making passive bioventing feasible. This section provides background information on conventional and passive bioventing, including advantages and limitations, and limited results from passive bioventing demonstration projects. Section 3 describes the criteria that should be considered to determine if passive bioventing is applicable for given site conditions; Section 4 specifies testing procedures and equipment required to demonstrate the feasibility of passive bioventing; and Section 5 details considerations for the full-scale design of a passive bioventing system.

2.1 CONVENTIONAL BIOVENTING

Bioventing is a process of injecting ambient air into water-unsaturated soils to promote the in situ bioremediation of petroleum hydrocarbon contaminants. Minimum requirements for the

successful application of bioventing include adequate soil gas permeability, adequate soil water content, suitable microbial population, and adequate control of the contaminant vapor plume (USEPA, 1994; Leeson and Hinchee, 1997). Delivery of ambient air into soils has been shown in controlled laboratory studies to accelerate the microbial metabolism of hydrocarbons into nontoxic byproducts, including carbon dioxide (CO_2), water, and microbial mass (NRC, 1993). Bioventing is applicable at sites where the subsurface is contaminated with aerobically biodegradable compounds, including most of the constituents found in gasoline, jet fuel, diesel fuel, and many other petroleum-based products (USEPA ORD, 1995). Bioventing is not applicable for most chlorinated solvents (e.g., tetrachloroethylene) or other halogenated compounds (e.g., polychlorinated biphenyls).

A subsurface gas-phase oxygen (O_2) concentration of less than 5% (volume or pressure basis) indicates that supplying oxygen through the injection of ambient air will stimulate resident aerobic microorganisms (Leeson and Hinchee, 1997); however, injecting air may lead to the spread of hydrocarbons from the contaminated region. Thus, the rate of air injection should be sufficient to meet microbial metabolic requirements but minimize the spread of volatile hydrocarbon contaminants (e.g., benzene) to areas outside the treatment zone. Bioventing does not rely significantly on volatilization of soil contaminants to achieve cleanup goals since contaminants are degraded in situ within water-unsaturated soil.

Conventional bioventing requires at least one electrically powered blower either to inject ambient air into or to extract soil gas from the subsurface. Extracting soil gas can potentially draw ambient air into the subsurface. A regenerative electric blower is normally used to inject air into contaminated soil via vent wells that are screened above the water table in water-unsaturated soils. Electric blowers inject air at rates between 15 and 30 cubic feet per minute (cfm), or 20,000 and 40,000 cubic feet per day (cfd), using low injection pressures of 10 to 30 in of water (2,500 to 7,500 Pa) to minimize the spread of volatile hydrocarbons while maximizing the rate of biodegradation. Conventional bioventing has been successfully demonstrated at DoD and other facilities (Miller et al., 1993; Leeson and Hinchee, 1997) and is included in the list of treatment technologies profiled in the *Remediation Technologies Screening Matrix and Reference Guide* (FRTR, 2002). The construction of bioventing systems is covered in the U.S. Air Force (AFCEE, 1996) and U.S. Army (USACE, 2002) design documents.

2.2 PASSIVE BIOVENTING

Passive bioventing uses the difference in gas pressure that develops between the atmosphere and the subsurface to drive air through vent wells and into the contaminated subsurface. Previous field tests have shown that changes in atmospheric or barometric pressure cause vent wells screened in water-unsaturated soil to inhale and exhale air, a process sometimes termed "barometric pumping" or "breathing" (Pirkle *et al*., 1992; Rossabi *et al*., 1993). During times of increasing barometric pressure, there is a positive pressure difference between the atmosphere and the subsurface, and air flows through the vent well into the subsurface (Figure 1). Air will flow from the subsurface and into the atmosphere during times of decreasing barometric pressure. The magnitude of the ensuing airflow rate is primarily a function of the rate of barometric pressure change, well screen depth and length, and the air permeability of the soil near the vent well screen (Zimmerman *et al*., 1997; Rossabi and Falta, 2002).

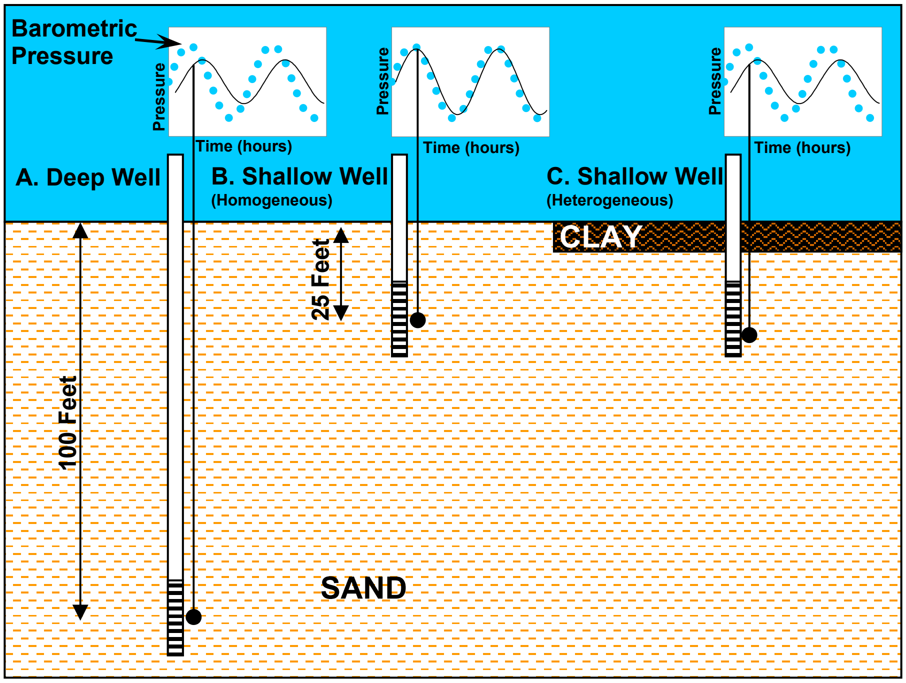

Figure 1. Air inhalation during times of increasing barometric pressure. Part A shows the vent well installed into unsaturated soil that is greater than 100 ft below ground surface (bgs). Part B shows a vent well installed at less than 25 ft bgs while Part C shows the vent well screened beneath a continuous layer of low permeability clay.

The difference in barometric pressure from day to night (diurnal) is on the order of 3 in of water (750 Pa). The passage of periodic weather fronts often causes an even greater change in barometric pressure with time. However, a significant change in barometric pressure alone is not sufficient to guarantee that air will flow between the atmosphere and subsurface. Specific subsurface lithologic and stratigraphic conditions must also exist for any change in barometric pressure to induce significant airflow through vent wells. Barometric pressure-induced airflow has been measured at sites with vent wells screened in air-permeable, contaminated soils that are isolated from the atmosphere by more than 100 ft of water-unsaturated soil, shown as the deep well configuration in Part A of Figure 1 (Rossabi et al., 1993; Hoeppel et al., 1995). Airflow through vent wells screened in shallow, air-permeable contaminated soils isolated from the atmosphere by a layer of low air permeability (Part C of Figure 1) has also been measured (Costanza and Rossabi, 2001). A thick (e.g., >100 ft) soil layer of high air permeability or a thin soil layer of low air permeability can retard the flow of air between the atmosphere and subsurface, leading to a gas pressure difference. While the magnitude of this naturally occurring pressure difference is low, between about 0.06 to 0.5 in of water (15 to 125 Pa), the rate of barometric pressure-driven airflow through vent wells can range from 0.5 to more than 50 cfm (Riha, 2001).

2.3 PREVIOUS TESTING OF PASSIVE BIOVENTING.

Passive bioventing has been demonstrated at three DoD and two Department of Energy (DOE) facilities in the contiguous United States (Table 1). With the exception of Castle Airport, these demonstrations were conducted in regions where the depth to groundwater was greater than 100 ft bgs with contaminants located in air-permeable soils with low water content.

Table 1 Previous Passive Bioventing Demonstrations

Location	Depth to Water (ft bgs)	Peak Airflow Rate (cfm)	Reference
Castle Airport, CA	50	20	ESTCP, 2000
Hanford, WA (DOE)	200	20	Ellerd *et al.*, 1999
Hill AFB, UT	100	5	Battelle, 1995
Savannah River Site (SRS), SC (DOE)	120	20	Rossabi *et al.*, 1993
Twentynine Palms Marine Corps Base (MCB), CA	200	7	Zimmerman *et al.*, 1997

At Castle Airport, the contaminated soil was beneath a laterally continuous clay/silt layer (greater than 90% silt/clay and 25.5% water by weight) approximately 20 to 25 ft bgs. This low permeability layer impeded the equalization of barometric pressure between the atmosphere and the air-permeable contaminated soils located at greater than 25 ft bgs, resulting in airflow through vent wells screened from 25 to 35 ft bgs (ESTCP, 2000).

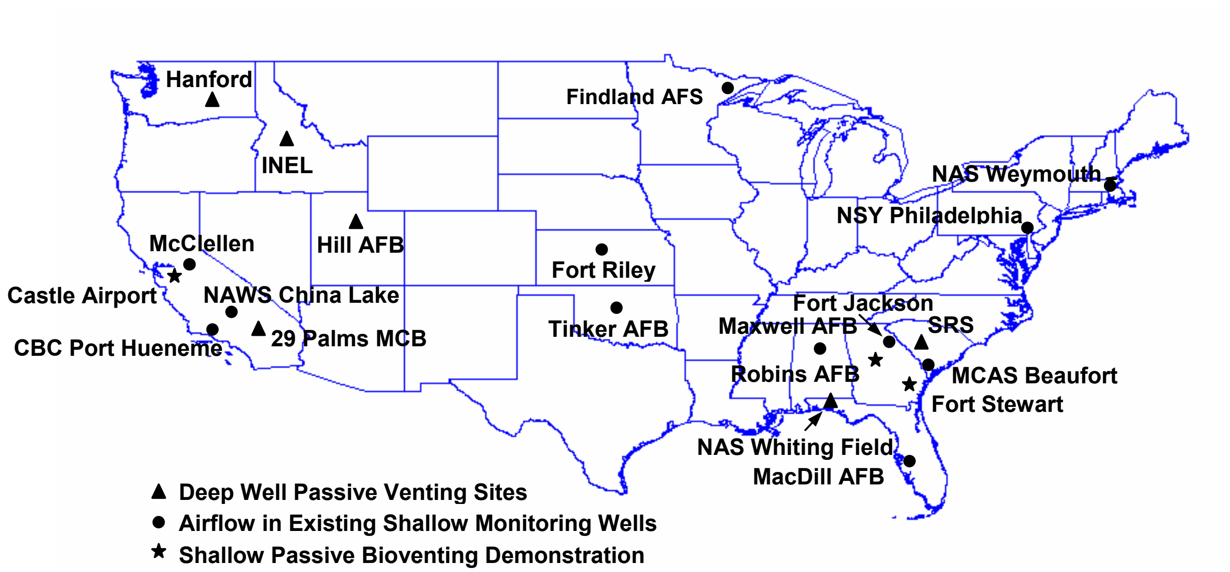

Figure 2 Location of passive bioventing demonstration sites. Deep well passive bioventing sites (▲), sites where airflow was measured in shallow groundwater monitoring wells (●), and sites where shallow vent wells were installed (★).

The favorable results observed at Castle Airport led to an effort to gauge the number of shallow groundwater sites in the contiguous United States where passive bioventing was feasible. The rate of airflow in existing groundwater monitoring wells was measured at 15 DoD sites shown in Figure 2 (ESTCP, 2004). Groundwater was within 15 ft of the ground surface at eight of the 15 sites, and silty-sand was the predominant water-unsaturated soil type at seven sites. Two of the 15 sites were covered with asphalt (MacDill Air Force Base [AFB] and Naval Shipyard [NSY] Philadelphia) while one site was covered with concrete (Fort Stewart). Hydrocarbon contaminated sand was overlain by a lower permeability soil (e.g., clay or silt) at four sites (McClellen AFB, Castle Airport, Maxwell AFB, and Fort Riley). Fractured rock contaminated with chlorinated solvents comprised the subsurface conditions at the former Finland Air Force Station (AFS). Airflow at each site was measured using an air-velocity transducer (TSI model 8475) installed in a 2-in diameter PVC pipe section that was attached to the top of an existing groundwater monitoring well (Figure 3). The air-velocity transducer was powered by a 12V battery that was recharged by two 10W solar panels. A Hermit 3000 datalogger was used to record air velocity, barometric pressure, and air temperature at 15-minute intervals over a period of 14 days. Of the 15 sites, three had passively induced peak airflow rates greater than 1 cfm, including Castle Airport, Tinker AFB, and Finland AFS (Table 2).

Figure 3 Picture of remote sensor and data logging system. An air-velocity transducer was mounted in 2-in outside diameter (OD) PVC piping attached to a groundwater monitoring well. A datalogger is located in the white box beneath the solar pane, and a 12V battery is contained in the blue tub.

Table 2. Summary of Airflow Measured in Existing Groundwater Monitoring Wells

DoD Installation (Name, State)	Measured Peak Airflow (cfm)	Lithology/Stratigraphy	Depth to Groundwater (ft bgs)
CBC Port Hueneme, CA	0.11	Silty sand	10
McClellan AFB, CA	<0.01	Silt over sand	60 (seasonal: 30-70)
NAWS China Lake, CA	0.08	Clay over silty sand	60
Maxwell AFB, AL	0.10	Clay over sand	24
Castle Airport, CA	15.00	Silt over sand	60 (seasonal: 10-70)
MacDill AFB, FL	0.25	Asphalt over silty sand	5
MCAS Beaufort, SC	0.18	Silty sand	10
Fort Stewart, GA	0.40	Concrete over silty sand	11.5
Robins AFB, GA	0.33	Silty sand	8
Finland AFS, MN	30.00	Fractured rock	60 (seasonal: 10-60)
Fort Jackson, SC	0.23	Silty and clayey sand	9-19
Fort Riley, KS	0.60	Clayey silt over sand	28
Tinker AFB, OK	1.20	Clay over silty sand	30
NSY Philadelphia, PA	0.23	Asphalt over sand	4
NAS Weymouth, MA	0.43	Glacial till	7

The survey of existing groundwater monitoring wells (Table2) suggests that airflow in shallow wells is not a widespread phenomenon. However, with the exception of the well located at Tinker AFB, none of the wells were designed to promote airflow. Groundwater monitoring wells are typically constructed with well screens that extend only a short distance above the water table into water-unsaturated soil. Fort Stewart and Robins AFB had subsurface soil conditions that were potentially favorable for passive bioventing, but the groundwater monitoring well screen sections at these two sites extended only into the capillary fringe where the air-filled porosity was limited. The presence of water in the pore spaces could have prevented or limited the amount of air that could flow into the subsurface given the small pressure driving force encountered during passive bioventing.

Vent wells were installed at Fort Stewart and at Robins AFB to evaluate the potential of using wells designed to maximize airflow. While there was an improvement in rate of airflow, the peak rate measured in the vent wells at Fort Stewart and Robins AFB was less than 1 cfm. The low airflow rate at Fort Stewart was attributed to low soil air permeability. Soil boring logs completed during the Resource Conservation and Recovery Act (RCRA) Facility Investigation Report (SAIC, 2000) indicated the presence of a potentially air-permeable pebble layer 11 to 13 ft bgs. A pebble layer was encountered during the installation of the vent well, but it consisted of a clay matrix surrounding the pebbles, rendering this layer low in air permeability. The low airflow rate at Robins AFB was attributed to the rapid, unrestricted movement of air through the shallow unsaturated subsurface soils (Part B of Figure 1), which limited airflow through the vent well. Further detail on the Fort Stewart and Robins AFB effort can be found in the Technology Demonstration Plan, Site-Specific Addendum (ESTCP, 2002).

2.4 ADVANTAGES AND DISADVANTAGES OF BIOVENTING.

Passive bioventing shares many of the same advantages and disadvantages as conventional bioventing summarized in the following list. Those features specifically pertinent to passive bioventing are highlighted in bold print.

Advantages of passive (and conventional) bioventing include:

- **Eliminates the need for electrical lines and outlets**
- **Avoids the use of an electric blower and associated operation and maintenance costs**
- **Eliminates the need for a vacuum manifold system and associated trenching costs**
- **Low pressure air injection minimizes volatile contaminant transport to receptors**
- Applicable to both the volatile and semivolatile fractions of hydrocarbon fuel mixtures
- Uses ambient air without pretreatment
- No above-ground off-gas treatment
- Uses resident aerobic microbes for treatment
- Utilizes conventional, readily available supplies and construction techniques
- Minimal operation and maintenance requirements

Disadvantages of passive (and conventional) bioventing include:

- **Passive bioventing requires more vent wells than conventional systems**
- **Permeable soils with high moisture levels may have limited airflow**
- Presence of low air permeability soils greatly limits or prevents oxygen transport
- Extremely low water content soils (e.g., <2% by weight) may limit microbial degradation
- Significant separate phase hydrocarbon fluid may inhibit microbial degradation
- Preferential pathways (sand layers/fractures) can impede airflow to contaminant zones
- Chlorinated hydrocarbons, not biodegraded aerobically, may be mobilized
- Requires thorough subsurface characterization, including soil air permeability testing
- Multiple years may be required to achieve cleanup goals

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3.0 SITE SELECTION

Sites where air has been observed flowing in monitoring wells are the most obvious choices for passive bioventing. Airflow is indicated by the sound air makes as it rushes through monitoring wells during the passage of storm fronts or at other times of changing barometric pressure. The sound of rushing air is often noted when collecting water samples and during routine well maintenance. However, passive bioventing may also be appropriate at a site even if airflow is not obvious because groundwater monitoring wells are not constructed to maximize airflow. Barometric pressure changes may induce airflow through a properly constructed vent well, depending on the thickness and permeability of the soil between the atmosphere and the contaminated subsurface and on the permeability of the materials near the vent well screen. The thicker the soil interval, the slower a change in barometric pressure is transmitted through the soil, resulting in a pressure difference between the atmosphere and subsurface (Part A of Figure 4). For example, barometric pressure inducted airflow rates ranging from 0.5 to more than 50 cfm have been measured in vent wells screened at greater than 100 ft bgs (Riha, 2001). A layer of low permeability soil or a perched water zone can also serve to delay barometric pressure transmission and induce a pressure difference (Part B of Figure 4). For example, barometric pressure induced airflow rates ranging from 0.1 to 30 cfm have been measured in vent wells screened within 30 ft of ground surface (Costanza and Rossabi, 2001).

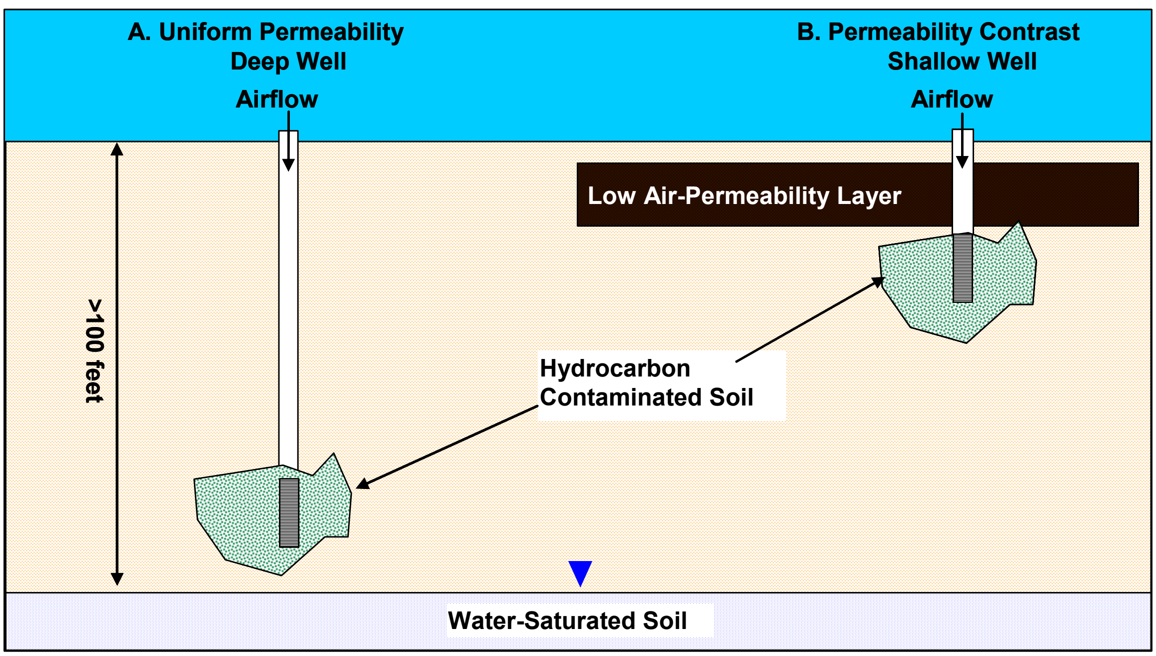


Figure 4. Successful passive bioventing subsurface archetypes. Part A shows the vent well installed into unsaturated soil that is greater than 100 ft bgs. Part B shows vent well screened beneath a continuous layer of low permeability, which could consist of clay soil or perched groundwater.

This section covers the site characteristics that should be evaluated to determine if passive bioventing is potentially applicable. The following sections describe how to estimate soil air

permeability based on soil type, the anticipated vent-well airflow rates based on barometric pressure changes, the airflow rate necessary to sustain biodegradation, and the expected radius of oxygen influence. The concluding section provides a summary of the subsurface conditions that if present, would justify a pilot test (go decision) or, if not present, would make the site an unlikely candidate for passive bioventing (no-go decision).

3.1 SOIL PERMEABILITY

Air permeability is the most important parameter to evaluate when considering bioventing as a remedial option. Air permeability is important because it controls the rate of airflow through soil as described by Darcy's equation modified for air:

$$v = \frac{k_{air}}{n_{air}\mu_{air}} \frac{dP}{dx} \tag{2.1}$$

where v is the airflow velocity (cm/s) in soil, k_{air} is the effective air permeability (cm^2), n_{air} is the air-filled porosity (cm^3 air/cm^3 total), μ_{air} is the air viscosity (g/cm s), and dP is the change in subsurface air pressure (g/cm s^2) over a distance x. Hydrocarbon contaminated soil must have sufficient radial air-permeability (k_{air}^{radial}) to allow air injected through vent wells to flow into surrounding soil and thus increase soil oxygen content (Figure 5). In contrast, the soil overlying the contaminated region must have relatively low vertical air permeability (k_{air}^{z}) to allow a pressure difference (dP) to develop in response to changes in barometric pressure.

Intrinsic permeability is a one-dimensional measure of the ease with which a fluid (i.e., air or water) flows through soil. Soil permeability is normally determined by measuring the rate of water flow through soil cores. However, soil intrinsic permeability can be estimated based on the type of soil present. Figure 6 shows the intrinsic permeability, in millidarcy, as a function of U.S. Department of Agriculture (USDA, 2003) soil textural classification. The USDA soil textural classification system uses the amount of sand- and clay-size particles, as determined from laboratory analysis of soil samples, to classify soil into one of 11 types shown in Figure 6. If soil classification data is based on visual inspection alone, then the permeability can be estimated using the descriptive terms such as "clay" that are normally found in monitoring-well boring logs. A commonly used rule of thumb is that the radial air permeability should be greater than 100 millidarcy (~1x10^{-9} cm^2) to allow the exchange of air in contaminated soils (USEPA, 1994; Leeson and Hinchee, 1997). In general, sandy soils are most suitable for passive bioventing.

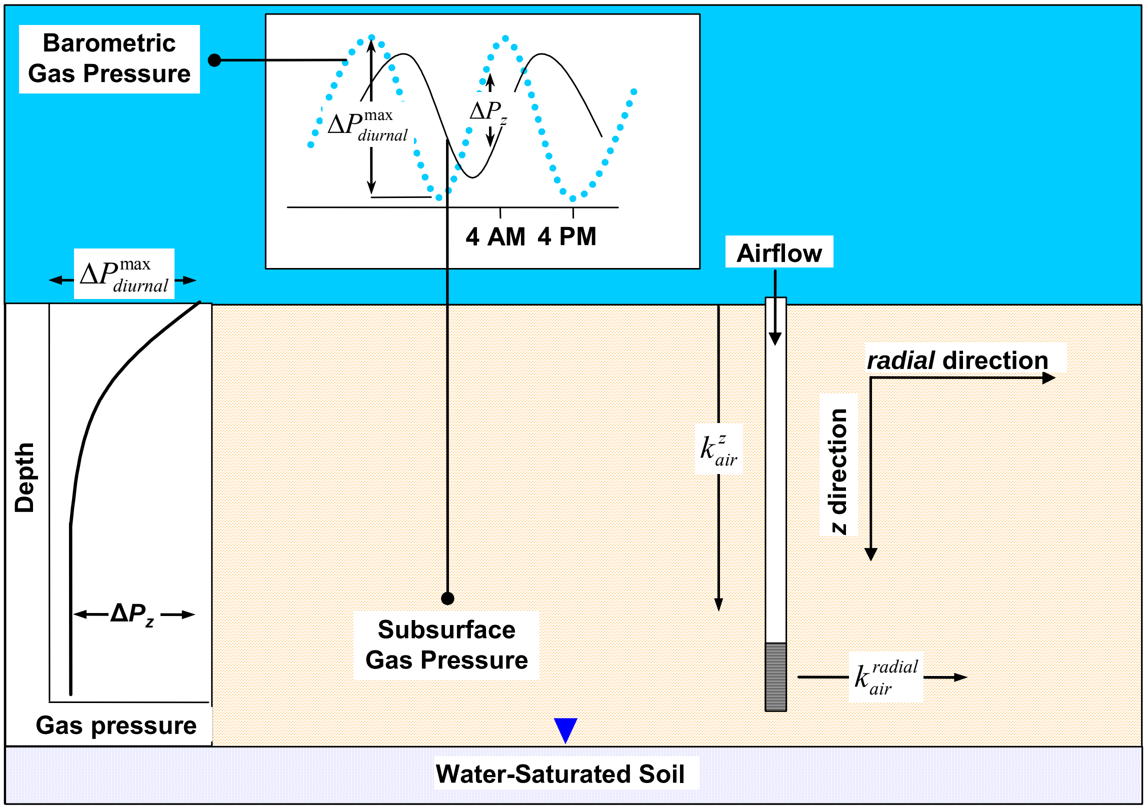


Figure 5. Radial and vertical air-permeability and subsurface gas pressure distribution.

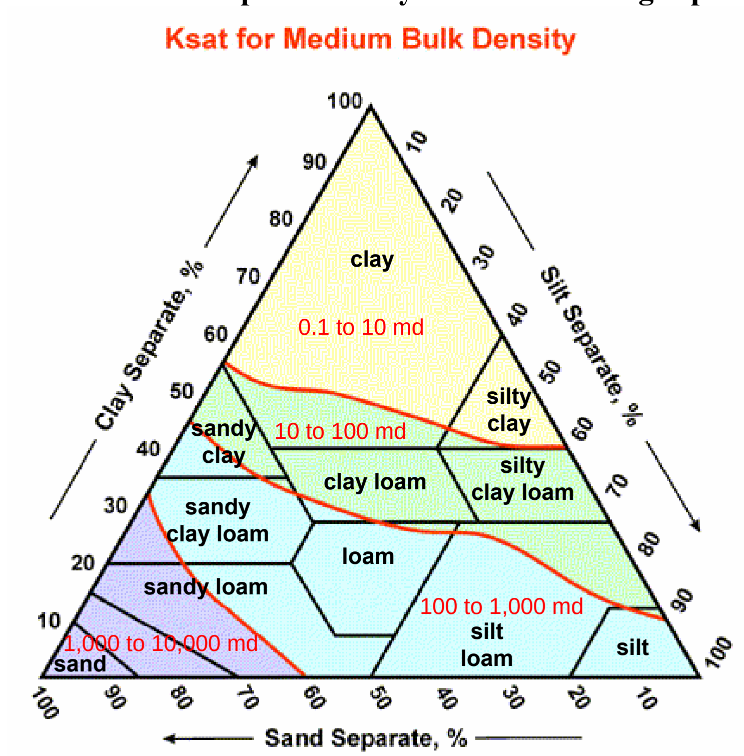


Figure 6. USDA soil classification with intrinsic permeability in millidarcy (USDA, 2003).

On a larger scale, the effective permeability across multiple horizontal soil layers is usually greater in the radial direction than in the vertical (i.e., anisotropic). The effective vertical permeability (k_{air}^{z}) for multiple horizontal layers of different soil types is limited to the layer with the least permeability (thickness weighted harmonic-mean), whereas the effective radial permeability (k_{air}^{radial}) is dominated by the most permeable layer (the arithmetic mean). Thus, the effective radial air permeability (k_{air}^{radial}) will normally be greater than the effective vertical air permeability (k_{air}^{z}) for all possible soil combinations given in Figure 6 (Freeze and Cherry, 1979).

The air permeability of soil also depends on the amount of liquid present in the soil pore spaces; the permeability indicated in Figure 6 is for soil that is saturated with air. However, aerobic microorganisms require water to support metabolic processes, including the degradation of hydrocarbons. A minimal soil water content of 2% by weight for sand was shown to adequately support in situ respiration (Leeson and Hinchee, 1997). As soil water content increases, there is a decrease in air permeability due to water obstructing the air-filled pore spaces. For example, Stylianou and DeVantier (1995) measured a 90% reduction in the air permeability of sand after increasing the water content from 5.1% to 21.8% by weight. Decreasing air permeability limits the rate of radial air flow into contaminated soils but may enhance the pressure differential by limiting the vertical flow of air in soils overlying the contaminated region (i.e., perched aquifer).

3.2 PREDICTING AIRFLOW IN VENT WELLS BASED ON SOIL TYPE

The first step in deciding if a site is suitable for passive bioventing involves reviewing soil boring logs and geologic cross sections to determine the soil types present. It is preferable to base the evaluation on the properties of the predominant soil types present, including porosity, dry bulk density, specific density, soil moisture content, and particle size distribution. The second step involves using theoretical relationships regarding the propagation of gas pressure through soil to estimate the pressure difference that could arise during a given change in barometric pressure. The final step uses the estimated pressure differential determined in the second step to predict the expected airflow rate through a well installed within the contaminated soil.

3.2.1 Predicting Differential Pressure

The change in subsurface air pressure with time can be estimated using a linearized pressure diffusion equation (Massmann, 1989):

$$\frac{\partial P_z}{\partial t} = \frac{k_{air}^{z} P_{avg}}{n_{air}\mu_{air}} \frac{\partial^2 P_z}{\partial z^2} \quad \text{or} \tag{2.2}$$

$$\frac{\partial P_z}{\partial t} = D_{eff} \frac{\partial^2 P_z}{\partial z^2} \text{ with } D_{eff} = \frac{k_{air}^{z} P_{avg}}{n_{air}\mu_{air}}$$

where P_z is air pressure within the subsurface and P_{avg} is the average barometric pressure. Equation 2.2 describes the diffusion of pressure through soil where the diffusion coefficient is proportional to the effective vertical air permeability. The analytical solution to Equation 2.2 is useful for predicting the pressure difference that could develop in response to a periodic change

in barometric pressure. Daily diurnal pressure changes can be described as a sinusoidal function of the form:

$$P_{atm} = \Delta P_{diurnal}^{\max} \sin\left(\frac{2\pi t}{T}\right) + P_{avg} \tag{2.3}$$

where $\Delta P_{dirunal}^{\max}$ is the maximum daily (diurnal) atmospheric pressure change, and T is the period over which the pressure changes, which is assumed to be 24 hours. The maximum subsurface pressure differential based on a solution of Equation 2.2 using the surface condition described by Equation 2.3 is given in Carslaw and Yaeger (1959) p. 64:

$$\Delta P_z = \Delta P_{diurnal}^{\max}\left[1 - \exp\left(-z\sqrt{\frac{0.123}{k_{air}^{z}}}\right) \times \sin\left(\frac{\pi}{2} - z\sqrt{\frac{0.123}{k_{air}^{z}}}\right)\right] \tag{2.4}$$

Equation 2.4 describes the maximum pressure difference (P_{atm}–P_z = ΔP_z) between the surface and subsurface as a function of depth below ground surface caused by a diurnal change in atmospheric pressure (see Appendix A for detailed derivation). Figure 7 shows a plot of Equation 2.4 for different effective vertical air-permeability values where the pressure factor (DP) is the ratio $\Delta P_z / \Delta P_{diurnal}^{\max}$.

Figure 2.4 suggests that a gas pressure difference between the atmosphere and subsurface can exist even in the most permeable soil (20,000 millidarcy). However, the pressure difference will be greatest at sites with an effective vertical permeability of less than approximately 100 millidarcy. This corresponds to the clay and silt type soils from Figure 6. Figure 7 demonstrates that a pressure differential is more likely to develop at sites with a low permeability layer (Part B of Figure 4), regardless of depth below ground surface. The thickness of the low permeable soil can be inferred from Figure 7; for example, a 5-ft-thick layer of 0.1 millidarcy soil would be required to achieve the maximum pressure differential (DP = 1) whereas a 15-ft-thick layer would be required for 10 millidarcy soil.

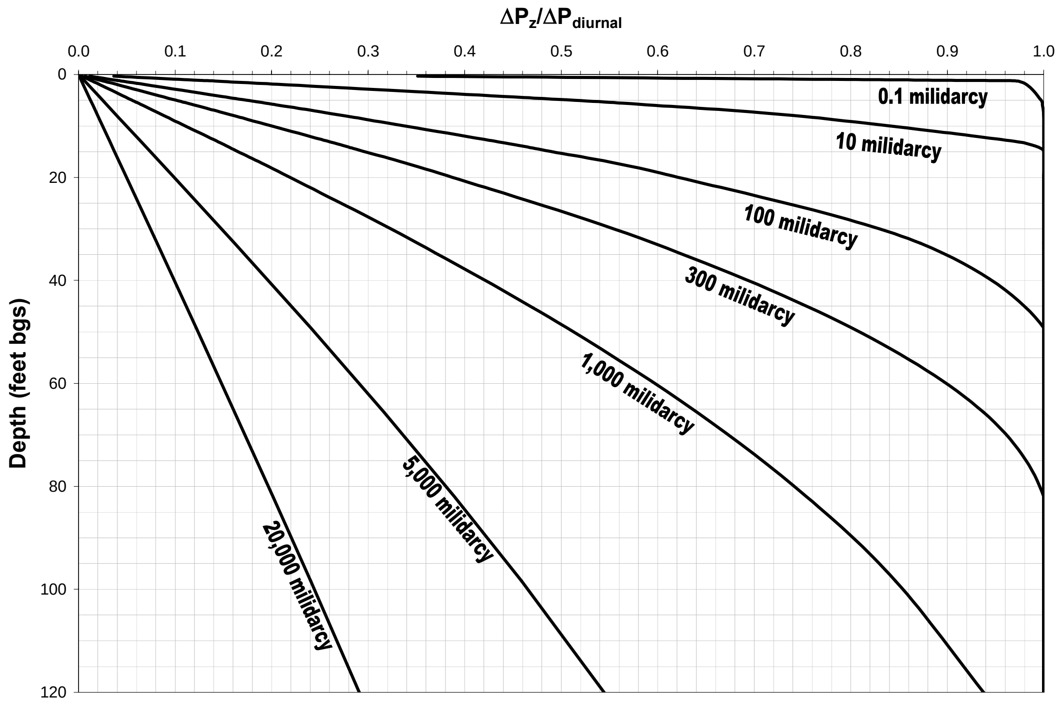


Figure 7. Calculated pressure factor (DP) with depth below ground surface as a function of vertical permeability (k_{air}^{z}).

3.2.2 Typical U.S. Diurnal Pressure Changes

The difference between the barometric pressure from day to night in the contiguous United States ranges from less than 0.01 to greater than 0.8 pounds per square inch (psi) (0.7 to 55 millibar [mbar]; 0.3 to 22 in of water), based on values reported in the Lawrence Berkeley National Laboratory (LBNL) meteorological database. The LBNL database contains the average daily pressure change based on 22 years of hourly data collected by the National Oceanic and Aeronautic Administration at 208 monitoring stations located throughout the United States (Apte *et al.*, 1998). The meteorological database was created for use in modeling indoor air quality.

Figures 8 through 11 show the distribution of the change in daily barometric pressure in the contiguous United States averaged over each of four seasons. The season averages were calculated using values from the LBNL meteorological database and interpolated using Groundwater Modeling System software (GMS, ver. 4.0). The southern portion of the United States tends to experience smaller daily pressure changes compared to the northern half. The greatest change in daily barometric pressure occurs in the cooler months of spring, fall, and winter. The symbols on Figures 8 through 11 refer to the location of passive bioventing locations shown on Figure 2.

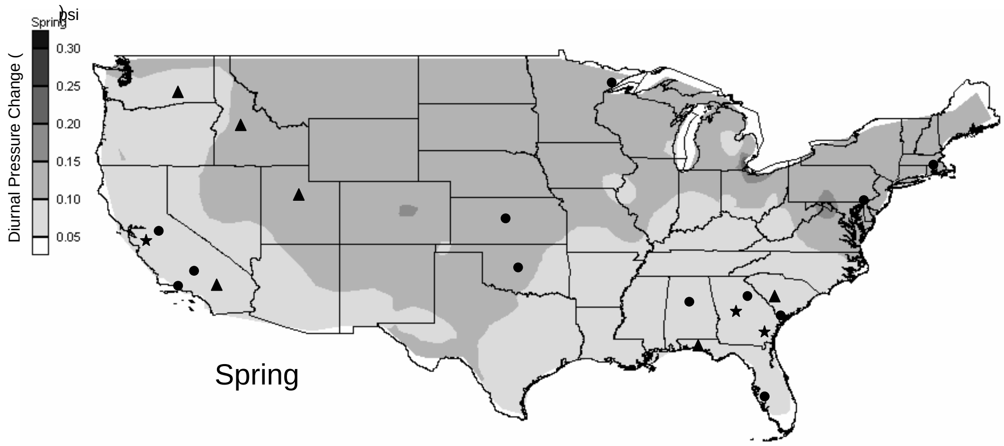


Figure 8. Average changes in daily barometric pressure (psi) for March, April, and May in the contiguous United States. Symbols indicate the location of passive bioventing pilot test sites (see Figure 2).

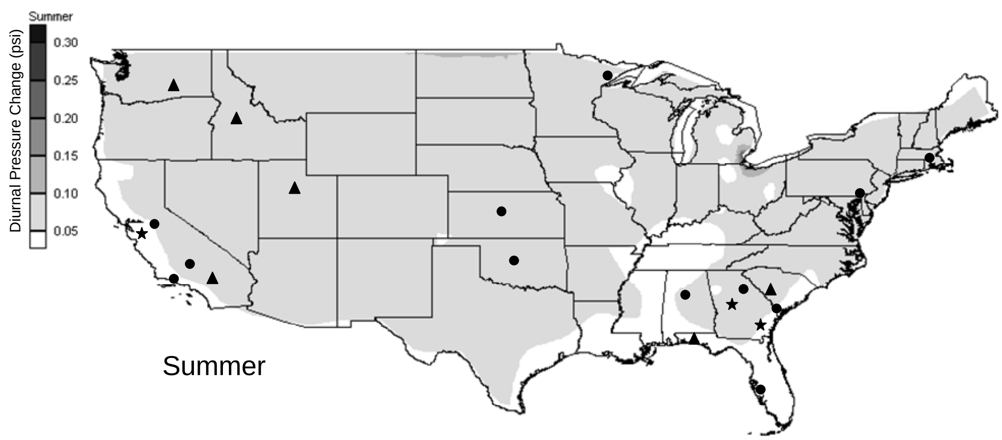


Figure 9. Average changes in daily barometric pressure (psi) for June, July, and August in the contiguous United States.

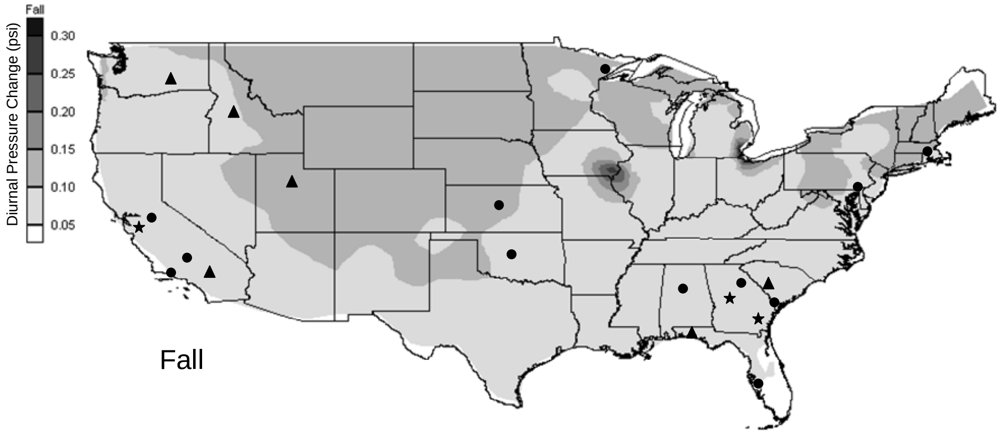
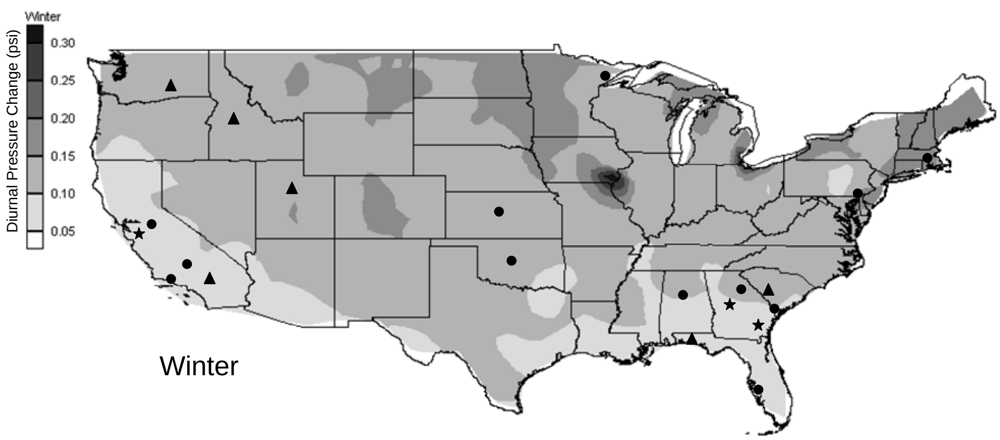


Figure 10. Average changes in daily barometric pressure (psi) for September, October, and November in the contiguous United States.



U.S. Map Source: U.S. Geologic Survey, 2002

Figure 11. Average changes in daily barometric pressure (psi) for December, January, and February in the contiguous United States.

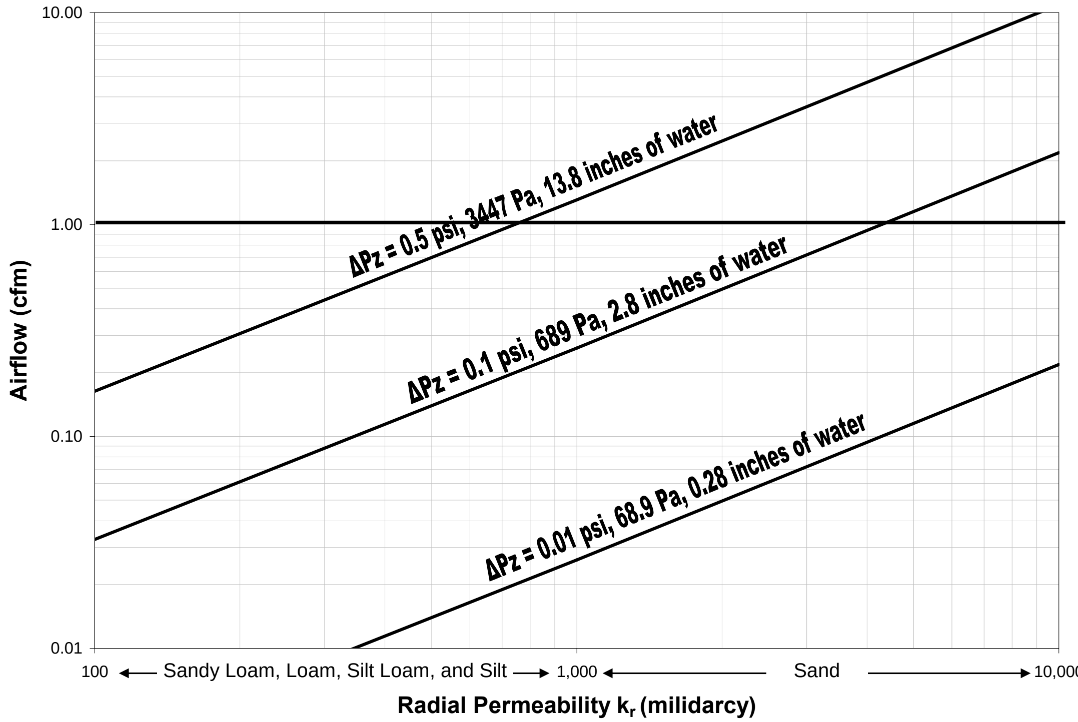


Figure 12. Airflow rate as a function of radial permeability and differential pressure (ΔP_z).

3.2.3 Predicting Airflow Rate

Rossabi and Falta (2002) derived and validated the following equation that can be used to estimate airflow through a vent well in response to differential pressure:

$$Q(t) = k_{air}^{radial} \Delta P_z \frac{0.0303}{\ln\left(49.32 \times k_{air}^{radial}\right)} \qquad (2.5)$$

where Q is the flow rate in cfm that can be expected from a vent well with a screen length of 10 ft due to a step pressure change of ΔP_z (psi) and k_{air}^{radial} is the radial air permeability (millidarcy). A detailed derivation of Equation 2.5 is provided in Appendix A, Section A.2. Figure 12 is a plot of Equation 2.5 for differential pressure (ΔP_z) as a function of radial air permeability.

Figure 12 demonstrates that vent-well airflow rates ranging from 0.01 to 10.00 cfm are possible given the average change in barometric pressure in the United States as shown in Figures 8 through 11. Soils with permeability of greater than 100 millidarcy include sandy loam, loam, silt loam, and silt, while sand is the only soil type with permeability of greater than 1,000 millidarcy (Figure 6).

3.2.4 Procedure for Estimating Airflow Rate

The preceding sections have described the parameters that are necessary to estimate the rate of airflow induced by changes in atmospheric or barometric pressure. Table 3 summarizes steps to follow using a combination of site-specific information and the figures provided in this

document to estimate the airflow rate for a site where passive bioventing is being considered as a remedial option.

Table 3. Steps to Estimate Passive Bioventing Airflow Rate

Step	Procedure	Estimated Value
1	Use the soil type information from soil boring logs to estimate the effective vertical air permeability from Figure 6. Chose the **least** permeable soil layer located between ground surface and the contaminated soil.	k_{air}^{z}
2	Estimate the DP factor using Equation 2.4 or Figure 7 based on the vertical air permeability from Step 1 and the depth below ground surface (*z*) of the contaminated soil.	DP
3	Estimate the diurnal barometric pressure change for the site based on Figures 8 through 11 and multiply by the DP factor found in Step 2 to estimate the maximum expected differential pressure.	ΔP_z
4	Use the soil type information from the soil boring logs to estimate the radial air permeability of the contaminated soil from Figure 6. Chose the **most** permeable soil layer of the contaminated zone.	k_{air}^{radial}
5	Use the pressure difference estimated in Step 3 and the radial permeability from Step 4 to estimate the airflow rate using Equation 2.5 or Figure 12.	Q

Unfortunately, soil permeability as estimated using visual descriptions of soil type differs from true effective permeability values by at least an order-of-magnitude. As a result, it is difficult to predict the barometric pumping performance of a vent well. Since radial permeability and differential pressure are the most important parameters that determine the rate of airflow in a vent well, measuring these two parameters is the only reliable method to determine the viability of passive bioventing.

3.3 AIRFLOW REQUIRED TO SUSTAIN AEROBIC BIODEGRADATION

The concentration of oxygen in soil gas must be maintained at greater than 5% to sustain aerobic biodegradation. This requires that atmospheric air (21% O_2) be delivered at a rate that is at least equal to the rate at which oxygen is consumed, or the oxygen utilization rate. Leeson and Hinchee (1997) suggest that the volume of subsurface gas at a site be exchanged with atmospheric air at least once a day to sustain aerobic biodegradation. The Army Corps of Engineers (USACE, 2002) suggests that only a fraction of the subsurface volume needs to be exchanged each day to sustain biodegradation. The rate of airflow required to exchange the gas in a subsurface volume every 12 hours (passive bioventing day) is described by the following equation:

$$Q = \frac{V}{12\ \text{hr}} = \frac{\pi R^2 H n_{air}}{720\ \text{min}} \tag{2.6}$$

where V is the subsurface gas volume to be exchanged, R is the radial distance from the vent well, H is the length of the well screen or vertical thickness of the subsurface volume, and n_{air} is the air-filled soil porosity. Figure 13 is a plot of Equation 2.6 and shows the rate of airflow

required to exchange one subsurface gas volume every 12 hours. For example, an airflow rate of 1 cfm for a period of 12 hours will exchange the gas within a 2,400 ft^3 subsurface volume with air-filled porosity of 0.3.

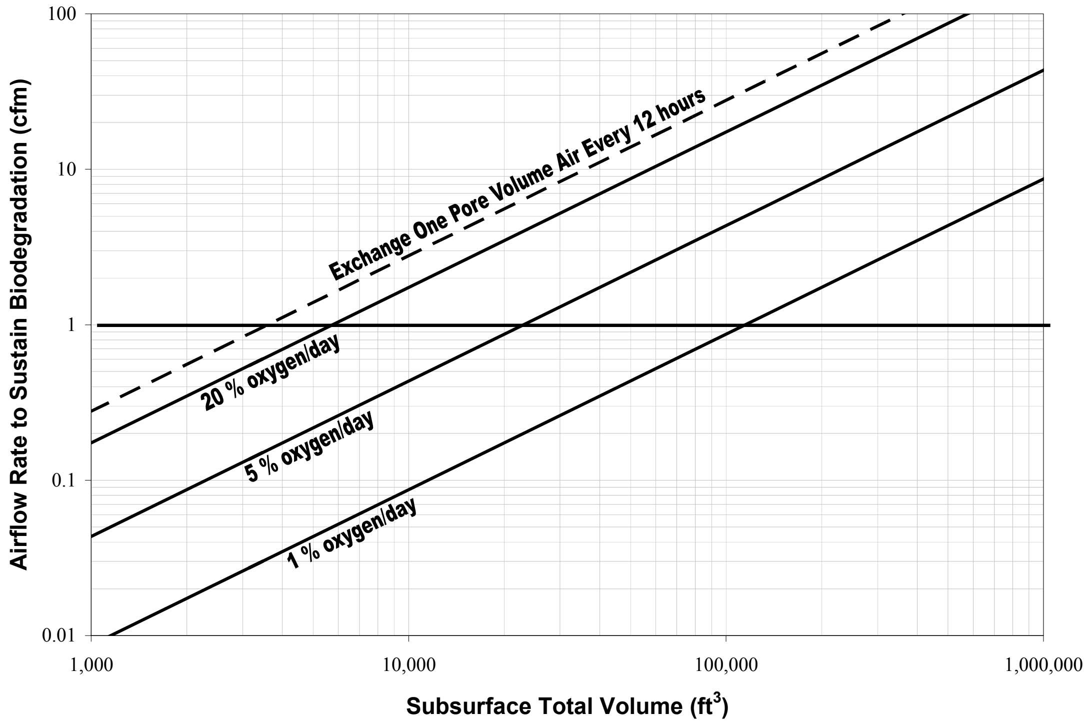


Figure 13. Airflow rate to sustain biodegradation in subsurface volume for 12-hour period.

Another way to estimate the airflow rate required to sustain biodegradation is to calculate the airflow required to meet an oxygen utilization rate. The oxygen utilization rate has been measured for many sites and generally ranges from 0.05 to 24%/day (Hinchee and Ong, 1992). Assuming that the measured utilization rate is a bulk term that accounts for the loss of oxygen due to diffusion in addition to the microbiologic consumption, then a simple analytic relationship can be used to estimate the airflow required to maintain an oxygen concentration of greater than 5%:

$$Q_{in} = \frac{720\,\mathrm{min}}{\mathrm{hr}} \frac{k_0 V n_{air}}{16} = \frac{720 k_0 \pi R^2 H n_{air}}{16} \tag{2.7}$$

where R is the radius at which the soil-gas oxygen concentration is greater than 5%, H is the well screen length (ft), and k_0 (%/day) is the oxygen utilization rate (see Appendix A, Section A.3 for derivation of Equation 2.7). The rate of airflow required to meet the oxygen utilization rate of 1, 5, and 20%/day as a function of subsurface volume is also shown in Figure 13. For example, an airflow rate of 1 cfm for 12 hours per day would be able to maintain an oxygen concentration greater than 5% in a volume of greater than 100,000 ft^3 with an oxygen utilization rate of 1%/day.

3.4 SITE SELECTION GO/NO-GO CRITERIA

The decision to perform a pilot-scale passive bioventing feasibility test should be based on the projected cost of a full-scale passive bioventing system versus the cost of a conventional bioventing system. The cost of a full-scale passive bioventing system is largely based on the number of vent wells required to sustain biodegradation in a subsurface volume. The number of wells is determined by the radius of oxygen influence of each vent well and the vent well spacing. The radius of oxygen influence achieved by a passive bioventing vent well will always be less than the radius achieved when injecting air using an electrically powered blower due to the lower airflow rate achieved by passive bioventing. In the absence of prior infrastructure, the cost of installing passive bioventing vent wells, if completed using conventional drilling methods, may exceed the cost of installing and operating a conventional bioventing system.

While the radius of oxygen influence is not readily predicted, it may be estimated for each passive bioventing vent well by rearranging Equations 2.6 and 2.7 to yield:

$$R = \sqrt{\frac{Q_{in} 720}{\pi H n_{air}}} \tag{2.8}$$

$$R = \sqrt{\frac{Q_{in} 16}{720 k_0 \pi H n_{air}}} \tag{2.9}$$

where Q has units of cfm, H is in feet, and k_0 is the oxygen utilization rate in %/day. Based on the expected airflow rate (Q) as estimated in Section 3.2.4 and the length of the vent well screen, a range for the radius of oxygen influence may be estimated.

A vent well radius of influence that is less than 10 ft (20-ft well spacing) is projected to result in a full-scale passive bioventing system that will cost more to install than a conventional bioventing system and, therefore, a pilot scale passive bioventing test may not be justified. However, if lower-cost direct-push vent well installation techniques are used instead of conventional drilling, a vent well spacing of less than 20 ft may be more cost effective than conventional bioventing.

Other site conditions that would preclude a pilot test include:

- Vertical air permeability of overlying soil greater than 1,000 millidarcy
- Radial air permeability of contaminated soil less than 100 millidarcy
- Water content of the contaminated soil greater than 10% by mass.

If the estimated radius of oxygen influence for each passive bioventing vent well is greater than 10 ft and the soil permeability and water content are favorable, then installation of a pilot test system, as described in the following section, would be justified.

4.0 PILOT TEST

The radius of vent-well oxygen influence along with the oxygen utilization rate should be determined during a month-long pilot test. These parameters are used in calculating the distance between vent wells, which is required for designing and estimating the cost of a full-scale passive bioventing system. Vent wells in a full-scale passive system should be spaced so that oxygen levels will be greater than 5% throughout the petroleum-contaminated region to stimulate biotic activity.

The pilot-scale test involves installing at least one vent-well and three VMPs in the contaminated region (see Figure 14) and monitoring the rate of airflow in the vent well along with the gas pressure and oxygen concentration in the sealed VMPs for at least one month. The airflow in the vent well and gas pressure and oxygen concentrations in the VMPs should all be measured using automated sensors and recorded at 30-minute intervals using a datalogger. Measuring airflow and subsurface pressure at 30-minute intervals is required to capture the intermittent airflow events, thereby improving the estimate for the total volume of air delivered to the subsurface. Airflow and pressure data are also used to calibrate a model that can be used along with easily measured subsurface and atmospheric gas pressures to predict the volume of air delivered to the subsurface and eliminate the need to measure airflow (see Section 4.5.3). The oxygen utilization rate is determined by closing the vent well and measuring the decrease in oxygen concentration within the VMPs over a period of up to one week. This pilot test, which includes installing wells, completing measurements, and documenting test results, is expected to be completed within a 3 month period.

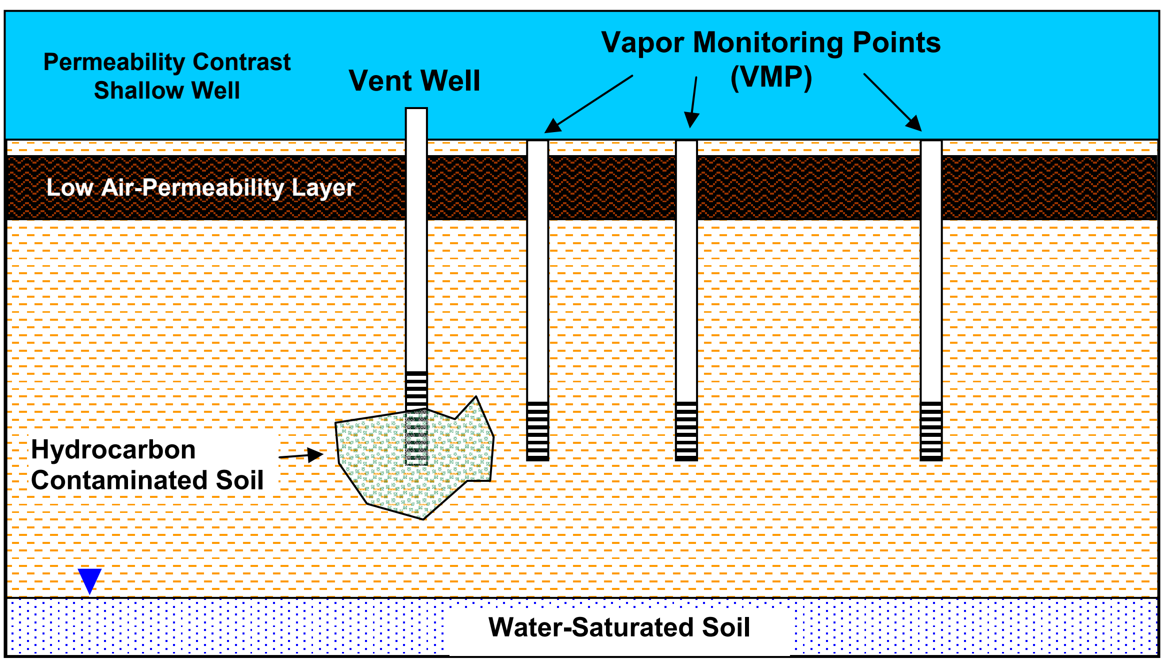


Figure 14. Vent well and vapor monitoring points (VMP) for a site with hydrocarbon-contaminated soil located beneath a low air-permeability layer.

A pilot test should be performed only at sites that meet the selection criteria given in Section 3 and have subsurface oxygen concentrations of less than 5% because there is little remedial benefit in delivering air to a hydrocarbon contaminated subsurface where the oxygen concentrations are already greater than 5% (Leeson and Hinchee, 1997). Therefore, the initial step of a pilot test is to perform a soil gas survey to determine the extent of hydrocarbon contamination and locate the subsurface region where the concentration of oxygen in soil gas is less than 5%. Vent wells and VMPs, if deemed appropriate, are then installed by the soil-gas survey contractor once the initial characterization is complete.

Table 3.1: Overview of Pilot Test Tasks

Task	Detail	Duration
1. Evaluation	Complete soil gas survey (Section 4.1). If O_2 < 5% and hydrocarbons present: proceed with Task 2, Installation. If O_2 > 5%: consider other remediation technologies (no-go decision).	1 week
2. Installation	Install vent well (Section 4.2)—keep sealed. Install vapor monitoring points with in situ oxygen sensors (Section 4.4.4). Install differential pressure sensors (Section 4.4.3). Install airflow sensor (Section 4.4.2).	
3. Baseline test	Seal vent well. Assemble datalogger and power supply, begin recording airflow, differential pressure, and in situ oxygen levels at 30-minute intervals. Establish steady-state oxygen levels.	1 week
4. Calibrate pressure-flow model	Open vent well to allow airflow. Collect data to determine radius of oxygen influence (Section 4.5.2) and calibrate pressure-airflow model (Section 4.5.3).	5 days
5. Aeration test	Install one-way valve (Section 4.3) to maximize oxygen distribution.	2 weeks
6. Oxygen utilization rate	Seal vent well. Determine oxygen utilization rate (Section 4.5.1).	3 days

4.1 SOIL GAS SURVEY

A soil gas survey consists of driving hollow steel rods into the subsurface and collecting samples of subsurface gas through holes in the tip of the lead steel rod. Gas samples are retrieved, as a function of subsurface depth, by pulling a vacuum on the interior of the hollow steel rods at fixed depths. The samples are collected into Tedlar bags. The concentration of volatile organic compounds, oxygen, and carbon dioxide within the Tedlar bag is then determined using portable analytical instruments. There are number of guides to performing soil gas surveys for bioventing, including Leeson and Hinchee (1997) and USACE (2002).

The one modification required for passive bioventing involves recording the vacuum pressure as the soil gas samples are being collected. Since less permeable soils will exhibit greater vacuum pressure while high permeability soils will have lower vacuum pressure, a relative permeability profile can be constructed based on the vacuum pressure for each gas sample. The permeability profile is a relative measurement rather than an absolute but is useful for selecting the depth and location to install a vent-well screen. For example, a layer with relatively low vacuum pressure (high permeability) that is contaminated with hydrocarbons, has low oxygen concentration, and

is located beneath a layer of high vacuum pressure (low permeability) would be an ideal location to install a vent-well screen (Figure 15).

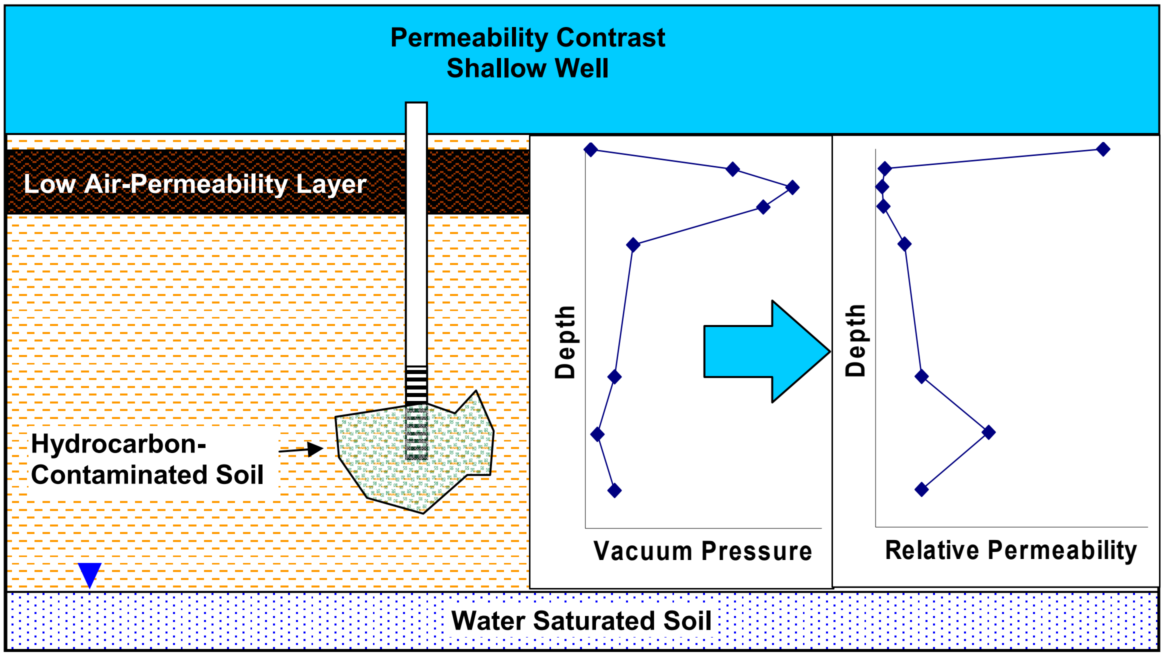


Figure 15. Vacuum pressure recorded at each soil-gas sampling depth. This information can then be used to estimate the relative air permeability at each sampling depth, assuming that the lowest vacuum pressure represents the greatest air-permeability value.

4.2 VENT WELL AND VAPOR MONITORING POINT CONSTRUCTION AND LAYOUT

As with conventional bioventing systems, vent wells are required to deliver air into the subsurface, and VMPs are used to monitor bioventing performance. Vent wells are installed with their intake screens located in the subsurface region, which is contaminated with petroleum hydrocarbons and has oxygen concentrations of less than 5%. The VMPs are installed with their intake screen at the same depth as the vent well and are located with increasing distance from the vent well (Figure 16). VMPs are often spaced in a radial pattern (Figure 16a) at distances expected to be under the influence of the vent well or along a line from the vent well (Figure 16b). The concentration of oxygen, carbon dioxide, and volatile contaminants is measured in vapor samples collected from the VMPs to determine the radius of oxygen influence and treatment volume.

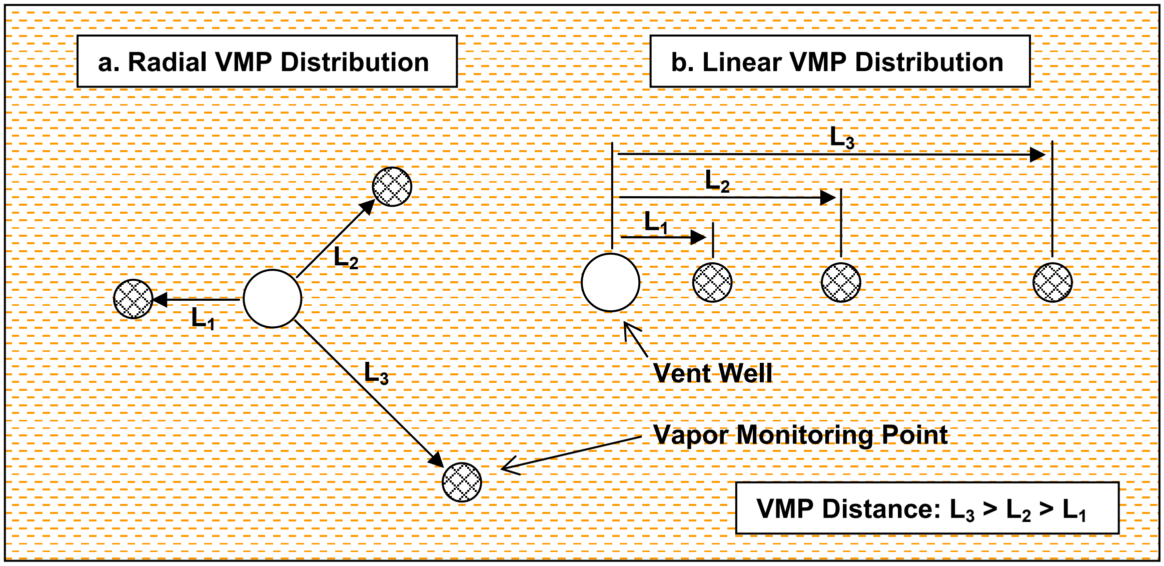


Figure 16. Radial and linear distribution of VMPs

Vent wells and VMPs may be installed using a variety of drilling or direct-push techniques. Some practitioners recommend that vent wells be constructed using traditional groundwater monitoring-well installation procedures (i.e., auger drilling) to prevent "smearing" of soil along the borehole wall that may occur when using direct-push techniques. The smearing of soil is thought to reduce the rate of airflow into the contaminated soil by reducing the effective radial gas permeability. However, there are no definitive tests that suggest any difference between well installation methods. The most important aspect of installing vent wells is that the screened portion of the well is located in the subsurface region that has the greatest radial gas permeability.

The standard guides for conventional bioventing systems recommend performing an in situ soil permeability test after installing a vent well to size the electrically powered blower and predict the radius of pressure influence (Leeson and Hinchee, 1997; USACE, 2002). However, since there is no blower to size for the passive bioventing, an in-well soil permeability test is not recommended. Instead, radial gas permeability as a function of subsurface depth (Figure 15) is preferred as this information will allow the vent well screen to be placed in the most permeable soil for maximum flow and pressure difference.

4.3 ONE-WAY PASSIVE VALVE

The one-way passive valve is used to control the direction of vent-well airflow, allowing air to flow into the vent well when the atmospheric pressure is greater than in the subsurface. The valve closes when the subsurface pressure is greater than atmospheric, preventing the exhalation of oxygen and volatile organic compounds. The operation of the one-way valve results in an expanding subsurface treatment volume through successive atmospheric-pressure driven air injection events.

Several one-way valve designs have been evaluated and are currently in use, including the Baroball®, horizontal membrane valve, and the vertical membrane valve. Figure 17 shows the

Baroball® that was developed by researchers at the Department of Energy's Savannah River Site, Aiken, South Carolina (U.S. Patent No. 5,641,245). The Baroball® valve is formed from a vertically oriented chamber having a conical shaped valve seat. A lightweight ball located in the valve chamber rests on the valve seat when atmospheric and subsurface pressures are equal. As orientated in Figure 17, air flows out of the subsurface when the subsurface pressure is greater than atmospheric pressure for a passive soil vapor extraction (SVE) application. The valve can also be inverted so that airflow is directed into the subsurface when atmospheric pressure is greater than subsurface pressure for passive bioventing applications.

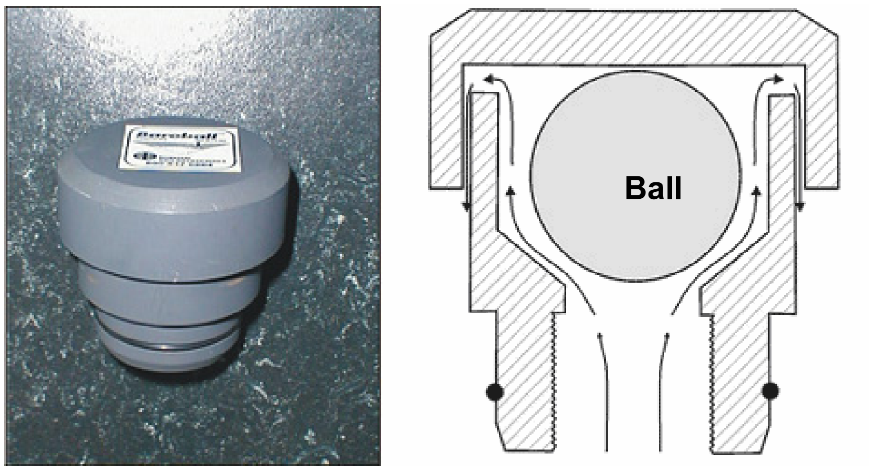


Figure 17. Picture and diagram of a Baroball® one-way passive valve (Christensen et al., 2003).

The advantages of the Baroball® are its compact size and use of inexpensive parts. Another compact and simple one-way valve was developed by researchers at the Idaho National Laboratory, Idaho Falls, Idaho, and is shown in Figure 18. This valve employs a lightweight plastic membrane that blocks airflow when seated on a rubber O-ring. The pressure required to close the membrane is less than that required to lift the ball in the Baroball®, indicating that over time more air would be introduced into the subsurface when using the membrane valve. However, the membrane is prone to lodge open and thus fail to control airflow, which may result in a decrease in subsurface oxygen content.

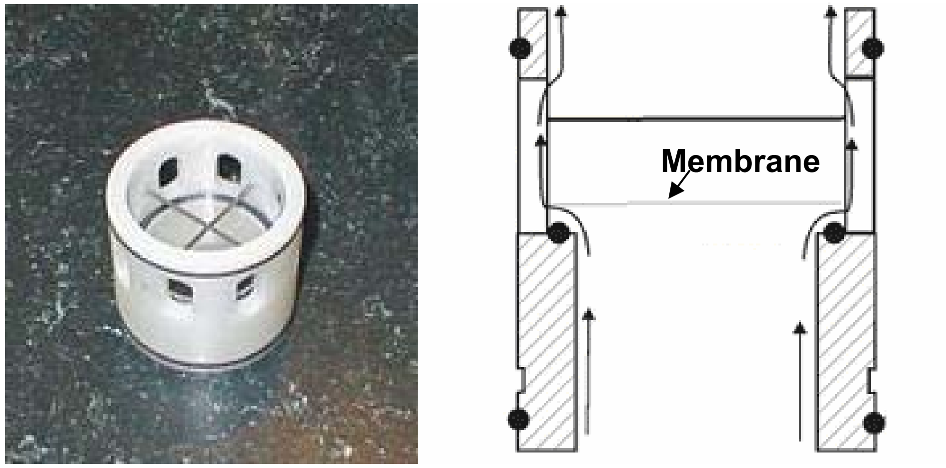


Figure 18. Picture and diagram of a compact horizontal membrane one-way passive valve (Christensen et al., 2003).

A larger one-way passive valve that also uses a membrane was developed by the Battelle Memorial Institute, Columbus, Ohio (Figure 19 and 20). The valve consists of a length of clear plastic pipe fitted with a perforated plastic plate that is aligned with gravity. A thin film of Mylar® sheet attached at the top of the perforated plate blocks the flow of gas from the subsurface when the atmospheric pressure is less than the subsurface pressure. The vertical membrane valve shown in Figure 19 has demonstrated its ability to consistently control the direction of airflow in field trials. However, this valve is larger than those shown in Figure 17 and 18 and extends at least 18 inches above the top of the vent well.

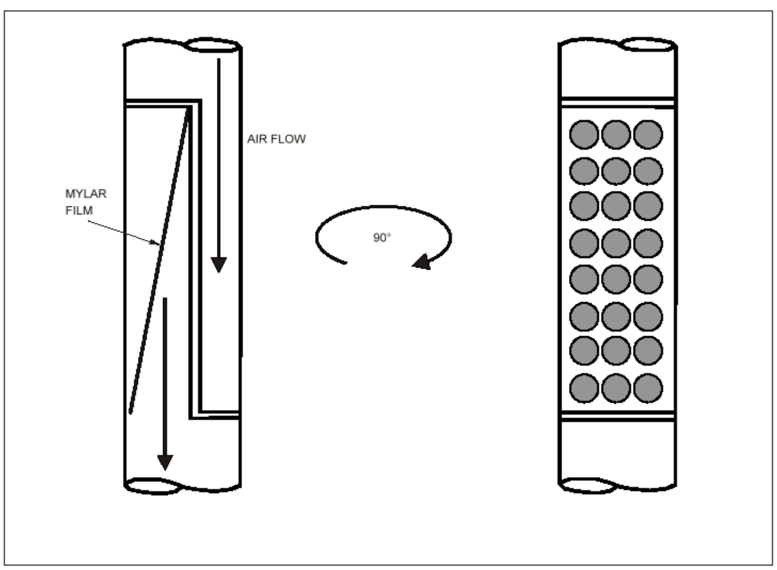


Figure 19. Diagram of a vertical membrane one-way passive valve.

4.4 MONITORING EQUIPMENT

Airflow rate, subsurface gas pressure, and oxygen concentrations are monitored after installing the vent well and VMPs. An automated data logging system connected to air-velocity and pressure sensors is recommended for determining the volume of air injected into or extracted from the subsurface during the pilot test period. Use of in situ oxygen sensors can result in accurate measurement of the oxygen utilization rate without having to station personnel at the site for 24- to 96-hour periods. Figure 21 is a schematic showing the layout of the automated-sensor datalogger system used during the Castle Airport passive bioventing demonstration (Figure 20). The sensors are powered from a standard 12V automobile battery that is recharged with a solar panel.

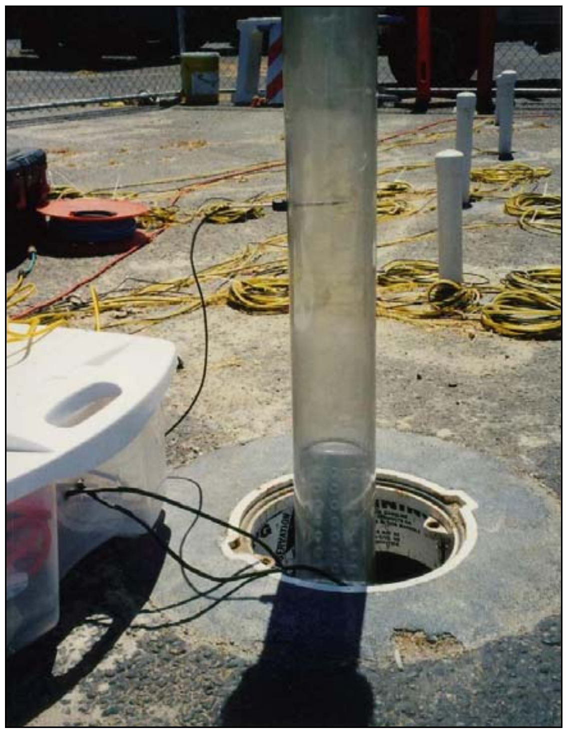


Figure 20. Picture of the automated monitoring system used during the Castle Airport passive bioventing pilot test.

4.4.1 Dataloggers

A datalogger is an electronic instrument that records sensor responses (e.g., voltage, amperage, resistance) at fixed time intervals. Dataloggers are small, battery-powered devices equipped with a microprocessor and data storage capacity that can be accessed and controlled using a personal computer. There are many commercial dataloggers, but it is beyond the scope of this document to review the features, advantages, and disadvantages of all the available models. The dataloggers used during the passive bioventing demonstrations completed to date were manufactured by Campbell Scientific, Inc. (CR21), In-Situ, Inc. (Hermit 3000), and Onset Computer (HOBO).

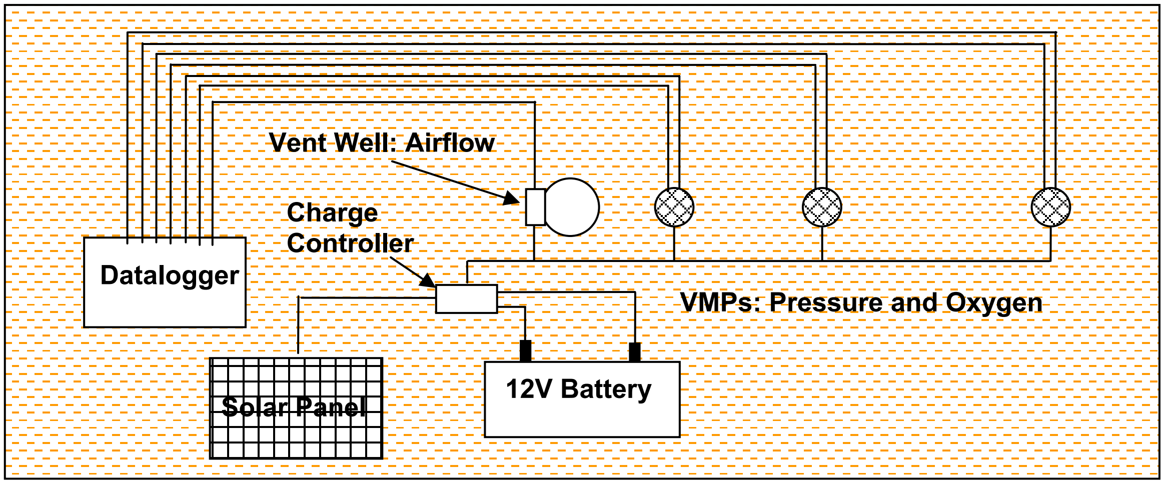


Figure 21. Diagram of an automated monitoring system.

4.4.2 Airflow Rate Measurement Techniques

Increasing the concentration of oxygen in the hydrocarbon contaminated soil is the most important result of bioventing. Given that the source of oxygen is the air flowing into the subsurface, then measuring the rate of airflow leads to estimates for the volume of oxygen injected or extracted during passive bioventing. Measuring airflow along with subsurface soil gas pressure is necessary for calibrating a model that can be used to predict the rate of airflow based on gas pressure alone. Also, measuring airflow rate is useful in evaluating the one-way valve performance to ensure that it is sealing during falling barometric pressure and allowing air to flow when barometric pressure is rising.

Airflow rates induced during passive bioventing are low relative to rates encountered during conventional bioventing or soil vapor extraction. Unfortunately, most of the airflow measurement techniques such as Pitot tubes or orifice plates are not suitable for such low airflows. While there are new airflow measurement techniques in development (e.g., ultrasonic), there are two types of airflow meters (i.e., anemometers) commercially available, including mechanical (rotary vane) and thermal (hot wire) anemometers, which are suitable for measuring the flows induced during passive bioventing. Mechanical anemometers can measure volumetric airflow rate (cubic feet per minute) and direction of airflow, whereas the thermal anemometers are limited to linear air velocity (feet per minute) without any indication of flow direction. However, the lowest airflow rate that mechanical anemometers can measure is approximately 80 ft per minute or 21 cfm in a 2-in diameter well casing, which is greater than the peak or maximum airflow rates measured at passive bioventing sites (Table 1). Thermal anemometers are capable of measuring airflow as low as 0.21 cfm in a 2-in diameter well casing and have been used during previous passive bioventing pilot tests.

The thermal anemometer sensor consists of a narrow diameter (0.25 in OD) probe that is inserted perpendicular to the path of airflow and is connected to an electronic enclosure which converts the analog probe reading to a digital air-velocity value. Figure 22 shows a thermal anemometer sensor installed in a section of pipe attached to a vent well, a configuration used to measure passive bioventing airflows during past pilot tests. Thermal anemometers measure the amount of

energy (i.e., electric power) required to maintain a heating element (hot wire or film) located at the tip of the probe at a constant temperature or they measure the temperature of the element at a fixed applied electric power (Baker and Gimson, 2001). Since thermal anemometers do not measure airflow directly, they require calibration to determine the velocity of a particular gas flowing by the heated sensor because each gas has unique heat transfer properties.

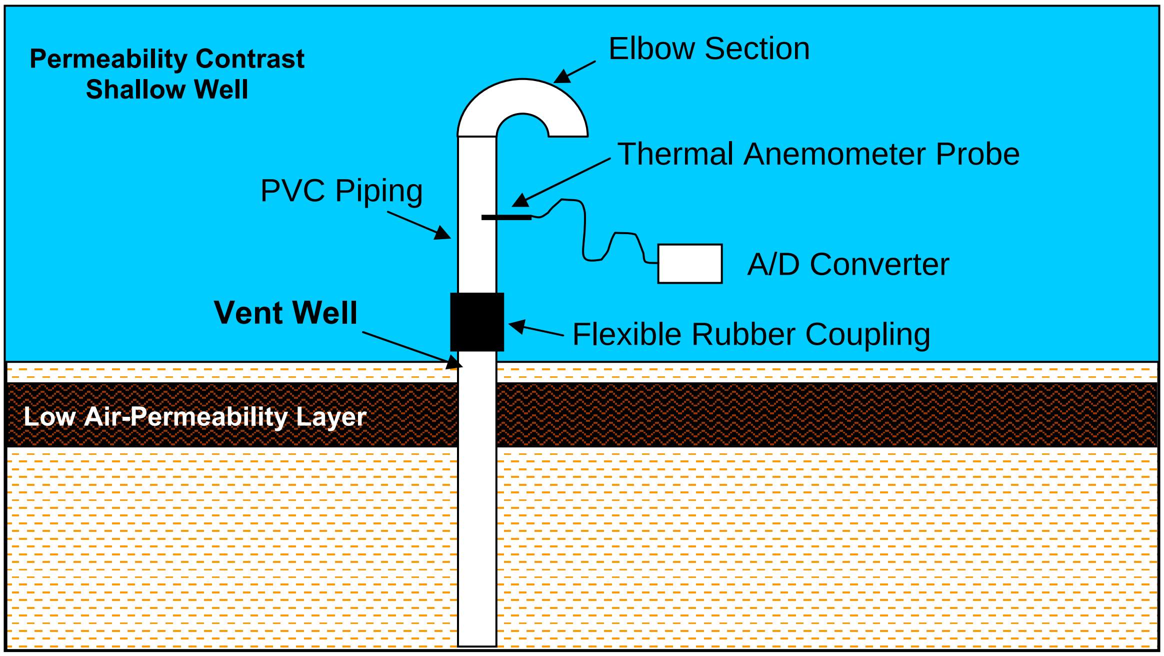


Figure 22. Diagram of thermal anemometer sensor installed in PVC piping attached to vent well.

Although thermal anemometers are capable of determining low airflow rates without obstructing the airflow path, thermal anemometers also have limitations that can affect the accuracy of the airflow rate measurement. The sensors are actually measuring the rate of heat transfer from the sensing element to the air flowing past the heated element. At very low flow rates, the heated sensor can produce convective flow (i.e., buoyant flow) of the gas near the sensor and yield false indications of airflow when none is occurring. Also, differences between the heat transfer properties of the air being measured and the air used to calibrate the sensor will affect the accuracy of the resulting measurement. Heat transfer properties of air are a function of temperature, barometric pressure (i.e., air density), water content (i.e., humidity), and air composition. Although most commercially available thermal anemometer sensors automatically compensate for changes in air temperature, there is no correction for changes in barometric pressure or air humidity. The error in air velocity due to changes in barometric pressure can be upward of 12% (Johnston and Fleeter, 1997) and upward of 13% due to changes in air humidity (Durst *et al.*, 1996).

Hot wire or film sensors are susceptible to errors when components of the fluid whose flow is being measured are condensable. For example, water vapor condensing and depositing as droplets on the heated probe can severely impair thermal sensor response. Several manufacturers have built devices that can tolerate these occasional sensor upsets and quickly return to their

normal response range. Some thermal sensors, however, cannot tolerate the occasional water drop so these sensors must either be protected or not selected for monitoring airflow during a passive bioventing pilot test.

Four of the manufacturers of thermal flow sensors appropriate for passive flow measurements are: Kurz Instruments (www.kurz-instruments.com/), TSI, Inc. (www.tsi.com), Sierra Instruments (www.sierrainstruments.com/index.html), and FCI, Inc. (www.fluidcomponents.com).

4.4.3 Differential Pressure Monitoring

Differential pressure refers to the difference between the gas pressure in the sealed VMPs and barometric pressure at any given moment. If the barometric pressure is greater than the pressure in the VMPs, then air is flowing into the subsurface through the vent well. Compared to measuring the rate of airflow, measuring air pressure is less problematic and the instrumentation used less expensive. While the pressure difference between atmosphere and subsurface may be measured using a simple water filled manometer, recording the pressure difference at 30-minute intervals over a 24-hour period is not practical with this technique. The use of automated differential pressure sensor is recommended to provide unattended pressure measurements that can be recorded by a datalogger.

The key parameter to consider when selecting a differential pressure sensor is the range of pressures the device is capable of measuring (dynamic range). This range should exceed the anticipated maximum change in barometric pressure but be narrow enough to resolve the small pressure changes that occur most frequently. Also, the pressure device must be capable of indicating both positive and negative (vacuum) pressure, often referred to as bidirectional, so the direction of airflow can be determined. Given that the maximum average barometric pressure change in the United States is 0.3 psi (see Section 3.2.2), a differential pressure sensor with the range of +0.3 to -0.3 psi (±21 mbar, ±8.3 in of water) would safely capture most of the pressure changes that typically occur. The differential pressure sensor should also automatically compensate for temperature changes expected to occur during daily heating and cooling cycles.

The other important consideration is the tubing used to connect the pressure sensor to the sealed VMP. Since the air within the tubing is isolated from atmospheric air, changes in temperature within the tubing can cause expansion or contraction of air inside the tubing and result in false indications of pressure changes. Tubing that is white or reflects light is recommended over clear tubing. The length of tubing used should be minimized and not placed directly in sunlight.

Figure 23 shows a diagram with a differential pressure sensor connected to three VMPs via a piping manifold system. This manifold arrangement is the least costly, but only the average pressure difference can be measured. Installing a dedicated pressure sensor in each VMP will increase pilot test costs but may provide valuable information about unequal pressure distribution.

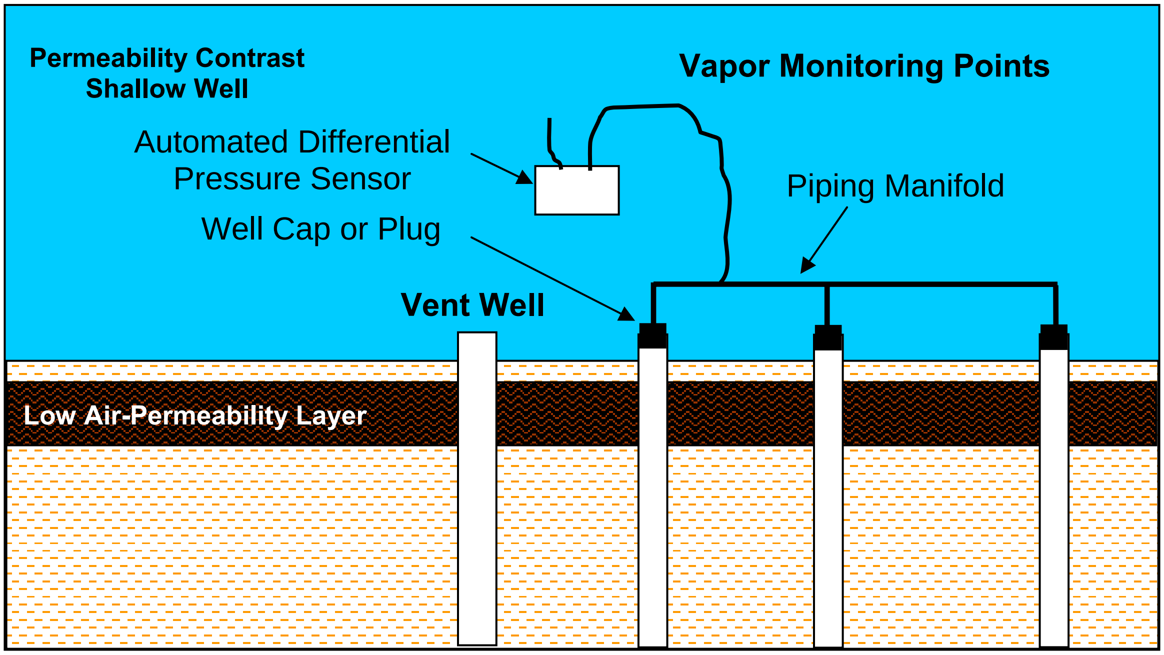


Figure 23. Diagram of a differential pressure sensor attached to three VMPs through a piping manifold system.

Past passive bioventing pilot tests have used differential pressure sensors, Model 607-3B manufactured by Dwyer (www.dwyer-inst.com) and Model XLdp – Ultra-Low by Ashcroft (www.ashcroft.com). However, there are a number of additional manufacturers of differential pressure transducers, including Kavlico Corp. (www.kavlico.com), Setra (www.setra.com), Vaisala (www.vaisala.com), Paroscientific (www.paroscientific.com), Mensor (www.mensor.com), and Omega (www.omega.com).

4.4.4 Oxygen Sensing

Identifying subsurface regions contaminated with petroleum hydrocarbons and soil gas oxygen concentrations of less than 5% is the goal of the soil gas survey described in Section 4.1. The purpose of measuring soil gas oxygen content during the pilot test is to demonstrate that passive bioventing is capable of increasing soil gas oxygen content, to determine the radius of oxygen influence from the vent well, and to measure the oxygen utilization rate. Subsurface oxygen content is an important measure of bioventing performance since it is the lack of subsurface oxygen which limits aerobic hydrocarbon degradation.

Measuring the oxygen content in soil gas samples vacuumed or pumped from VMPs has been accomplished using handheld portable gas detectors (Leesen and Hinchee, 1997; USACE, 2002). However, this method is labor intensive and requires stationing personnel at the site to collect at least hourly measurements during the initial 24 to 96 hours after opening the vent well to the atmosphere in an effort to demonstrate that subsurface oxygen content is increasing. The frequency of subsurface gas sample collection can be decreased to once per week after steady-state oxygen levels have been achieved. Another intensive sample collection event is required to

determine the oxygen utilization rate and involves measuring oxygen concentrations every hour for a 24-hour period after closing the vent well at the end of the aeration period.

An alternative approach is to install a dedicated oxygen sensor inside each VMP. Li and Lundegard (1996) reported that the cost of installing dedicated in situ oxygen sensors was less than the cost of stationing personnel on site when determining the oxygen utilization rate. The use of dedicated subsurface oxygen sensors is justified, despite the extra initial cost associated with the purchase and installation of each sensor, because oxygen concentrations are vital for determining the success of a passive bioventing application. For example, if uncertainties in measuring airflow rate or subsurface pressure lead to concerns that oxygen delivery was not sufficient to sustain hydrocarbon metabolism, then the in situ oxygen sensor data, which is recorded every 30 minutes, is available for review.

In situ oxygen sensors are available from J&S Instruments, Inc., Springfield, Ohio (http://www.jsinstruments.com/biorec.html).

4.5 PILOT TEST DATA ANALYSIS

After completing the tasks listed in Table 4, the airflow rate, pressure, and oxygen levels recorded by the datalogger are retrieved for analysis to determine the oxygen utilization rate and the radius of oxygen influence and to calibrate the pressure-airflow model.

4.5.1 Oxygen Utilization Rate

The oxygen utilization rate is the rate at which oxygen is consumed after being introduced into the subsurface. The rate of oxygen consumption is not necessarily due to biologic activity alone but also reflects oxidation of reduced minerals (e.g., sulfide [S^{-2}], ferrous iron [Fe^{+2}]), and loss through diffusive transport (Hinchee and Ong, 1992). However, the oxygen consumption rate is useful for estimating the rate of airflow required to maintain oxygen levels at greater than 5%.

The oxygen utilization or oxygen consumption rate is equal to the coefficient of a zero-order chemical reaction model described by the following equation:

$$\frac{dC}{dt} = -k_0 \qquad (3.1)$$

where dC is the change in gas-phase oxygen concentration with time (dt) and k_0 represents the zero-order rate coefficient with units of % per day. The zero-order rate coefficient (k_0) is equal to the slope of an oxygen concentration versus time plot as determined using a linear regression analysis (Figure 24).

Figure 24 shows an example graph used to determine the oxygen utilization rate from oxygen concentration data collected during the Castle Airport passive bioventing demonstration. The oxygen utilization rate ranged from 0.66%/day in a VMP located 8 ft from the vent well to 0.71% in the VMP that was 16 ft from the vent well, where the oxygen concentrations were above the 5% minimum value.

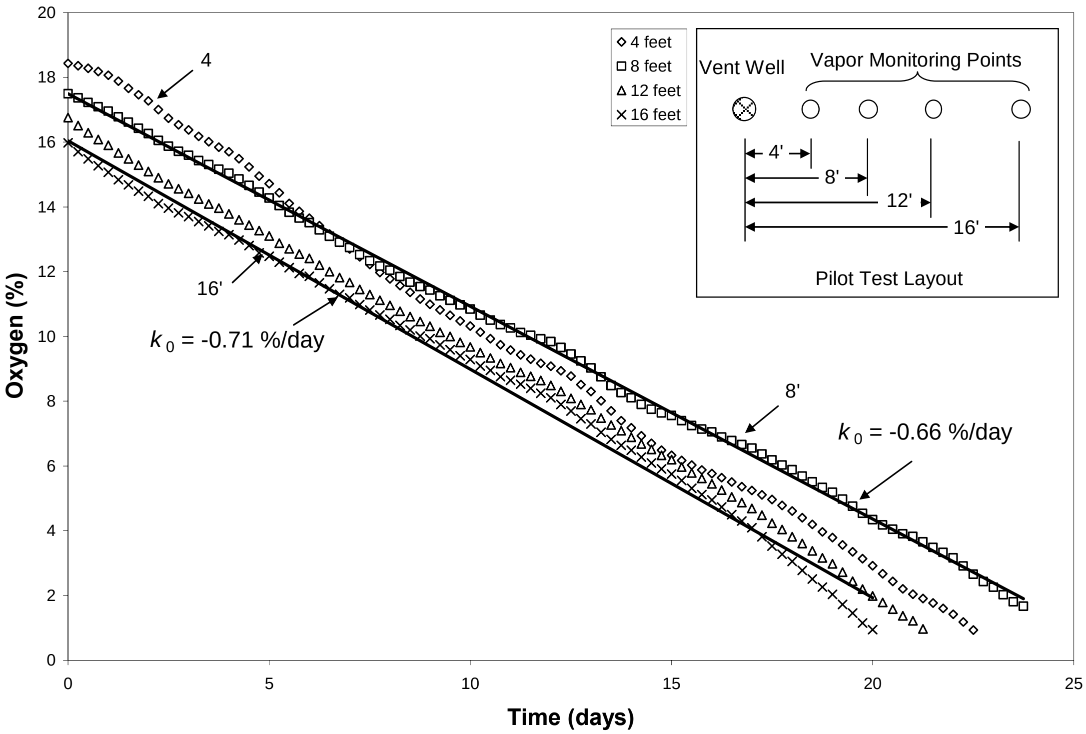


Figure 24. Concentration of oxygen at four subsurface locations recorded using in-situ oxygen sensors during the Castle Airport passive bioventing demonstration. The oxygen sensors were located 4, 8, 12, and 16 feet horizontally from the vent well.

4.5.2 Radius of Oxygen Influence

The radius of oxygen influence is the radial distance from the vent well, where the soil gas oxygen concentration is assumed to be 21%, to the point at which the soil gas oxygen concentration is 5%. Ideally, the VMPs will have been spaced so that there is 5% oxygen at the location farthest from the vent well at the end of the aeration test period. However, that may not be the case, and the radius of oxygen influence will have to be estimated. There are two approaches to estimating the radius of oxygen influence. The first is based on the rate of airflow required to exchange the gas in a subsurface volume every 12 hours (passive bioventing day) and is described by the following equation:

$$R = \sqrt{\frac{Q_{in} 720 \min}{\pi H n_{air}}} \tag{3.2}$$

where R is the radial distance from the vent well, Q_{in} is the rate of airflow into the passive bioventing well, H is the length of the well screen or vertical thickness of the subsurface volume, and n_{air} is the air-filled soil porosity. The radius of oxygen influence can be determined using the airflow rate alone; no information about the oxygen distribution is required.

The second approach for estimating the radius of oxygen influence assumes a radial oxygen distribution and utilizes the oxygen utilization rate to estimate the airflow required to maintain an oxygen concentration of greater than 5% and is determined using the following equation:

$$R = \sqrt{\frac{Q_{in}16}{720k_0 \pi H n_{air}}} \tag{3.3}$$

where R is the radius at which the soil-gas oxygen concentration is 5%, Q_{in} is the rate of airflow into the passive bioventing well, H is the well screen length (feet), and k_0 (%/day) is the oxygen utilization rate (see Appendix A, Section A.3, for the derivation of Equation 3.3).

4.5.3 Pressure-Airflow Model

Measuring both airflow and differential pressure is necessary for calibrating a simple analytical model that was developed to predict airflow based on differential pressure alone (Rossabi and Falta, 2002). Once calibrated, this simple model can be used to estimate airflow using data from the inexpensive and durable pressure sensors (see Section 4.4.3). The analytic model is an equation that relates airflow to differential pressure:

$$Q(\mathrm{t}) = H \frac{4\pi}{\mu_{air}} \frac{k_{air}^{radial} \Delta P_z}{\ln[2.25 \Delta \mathrm{t} \alpha]} \tag{3.4}$$

where Q is the airflow rate that can be expected from a vent well with a screen length of H due to a differential pressure of ΔP_z with air of viscosity μ_{air}. The time change (Δt) is equal to the interval between differential pressure measurements or 30 min (1,800 sec). The term α contains additional parameters:

$$\alpha = \frac{k_{air}^{radial} P_{avg}}{n_{air} \mu_{air} r_w^2} \tag{3.5}$$

where P_{avg} is the average atmospheric pressure, n_{air} is the air-filled soil porosity, and r_w is the radius of the vent well. The term k_{air}^{radial} is air permeability in the radial direction and is the parameter that must be determined by fitting measured airflow and differential pressure data.

Table 5. Recommended Parameters for Pressure-Airflow Model

Term	Value	Unit	Definition
P_{avg}	101,325	kg/m s^2 (Pascal)	Average atmospheric pressure
n_{air}	0.3	cm^3/cm^3	Air filled porosity
μ_{air}	1.83×10^{-5}	kg/m s	Viscosity of air at 18^{o}C
r_w	0.0245	m	Radius of standard 2 in diameter well
Δt_i	1,800	sec	Differential pressure measurement interval
k_{air}^{radial}	1×10^{-12}	m^2	Initial guess of radial permeability

The model calibration procedure begins after collecting airflow and differential pressure data at 30-minute intervals over a period of at least 5 days. The data is then arranged using spreadsheet, database, or numerical analysis software so that time comprises the independent data, with airflow and differential pressure as the dependent data. The values for the average atmospheric

pressure (P_{avg}), air-filled soil porosity (n_{air}), air viscosity (μ_{air}), radius of the vent well (r_w), differential pressure measurement interval (Δt), and radial air permeability (k_{air}^{radial}) are fixed to the recommended values provided in Table 4.

Airflow is then calculated for each differential pressure measurement using Equations 3.4 and 3.5. The calculated airflow is compared to the measured airflow, and the radial air permeability value (k_{air}^{radial}) is adjusted until calculated and measured airflows match. The closeness of the calculated and measured airflows can be determined using the sum of squared error (SSE) approach which involves calculating the difference between values, squaring the difference, and then summing all the squared errors for the dataset. The square root of the sum of squares represents an estimate of the closeness between the calculated and measured airflows where the smaller the SSE value the closer the calculated is to the measured airflow value.

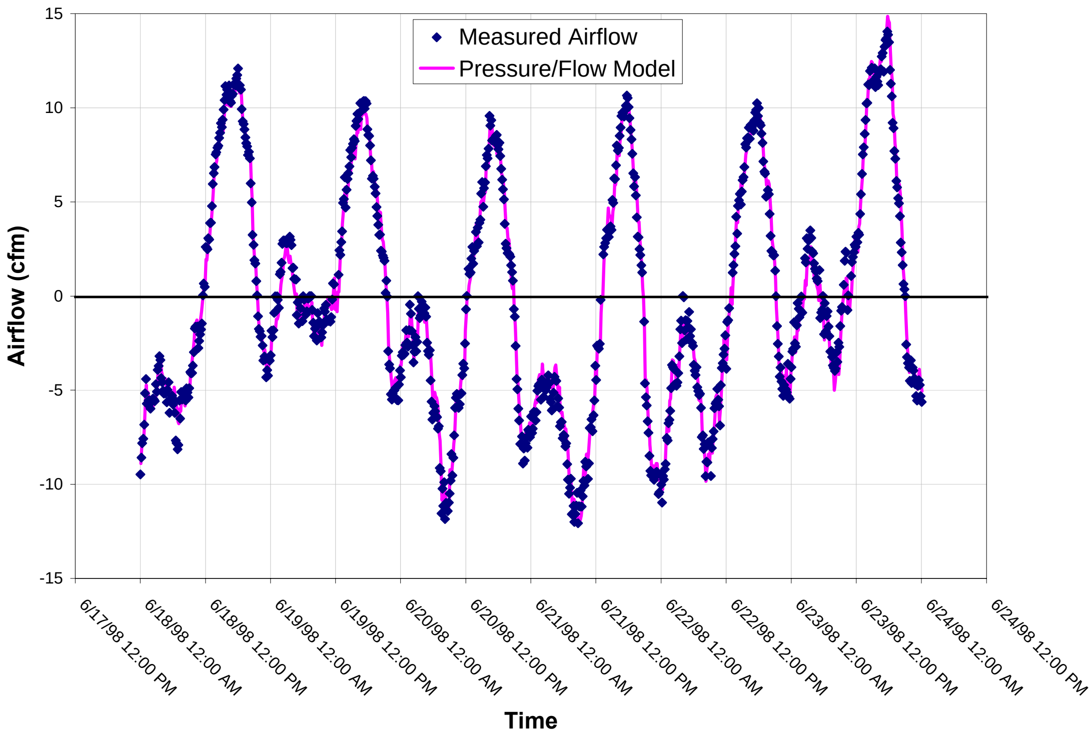


Figure 25. Calculated and measured airflow from the Castle Airport passive bioventing demonstration. The SSE was 42.7 with a radial air permeability of 8.72×10^{-10} m^2.

Figure 25 shows an example of the agreement between the measured and calculated airflow values obtained with data from the Castle Airport passive bioventing demonstration. A radial air permeability 8.72×10^{-10} m^2 or 880,000 millidarcy was required to calibrate the pressure/flow model for this dataset.

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5.0 FULL-SCALE DESIGN

Implementing a full-scale passive bioventing system involves installing additional vent wells and vapor monitoring points over those installed during the pilot test so that oxygen levels can be sustained at greater than 5% throughout the region contaminated with hydrocarbons (Figure 26). Full-scale system design should be based on the principles established for conventional bioventing systems, which are provided in the Air Force's Bioventing Design Tool (AFCEE, 1996), the Bioventing Cost Estimator (NFESC, 1996), and the U.S. Army Corps of Engineers Soil Vapor Extraction and Bioventing Engineering and Design Manual (USACE, 2002). The following sections address specific details regarding the design of passive bioventing systems, including vent well spacing and layout, and performance monitoring.

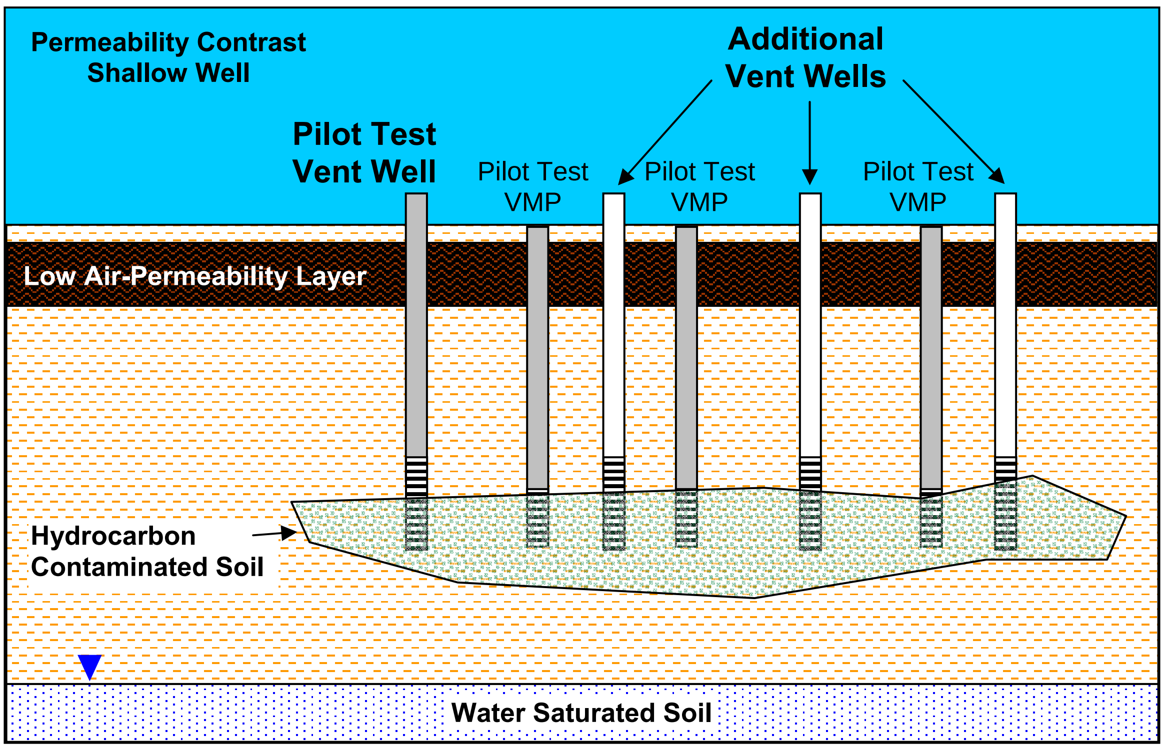

Figure 26. Additional vent wells added to site after completion of pilot test.

5.1 VENT WELL SPACING AND LAYOUT

Vent well spacing and layout refers to the distribution and number of wells required to increase and sustain oxygen levels at greater than 5% throughout the hydrocarbon contaminated region. Vent wells can be spaced in an offset pattern (Figure 27) to maximize the subsurface area influenced by each well or using an in-line pattern (Figure 28) to minimize the number of wells needed to cover the contaminated area.

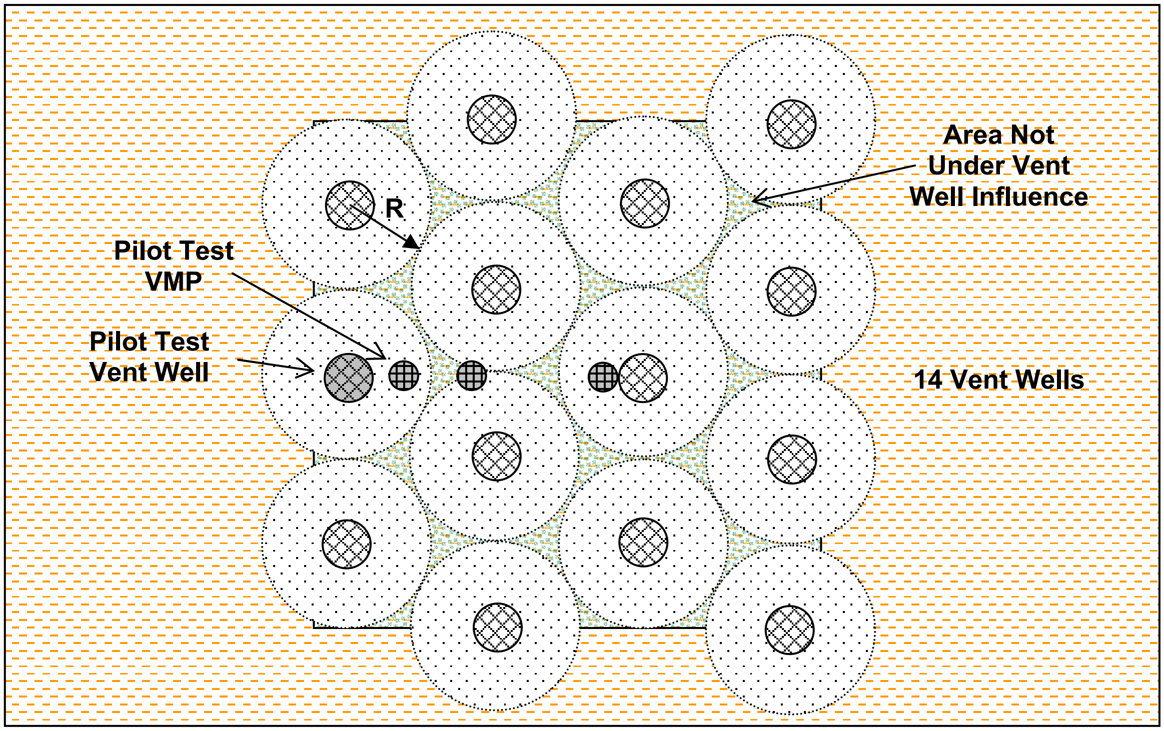

Figure 27. Vent wells spaced in offset pattern.

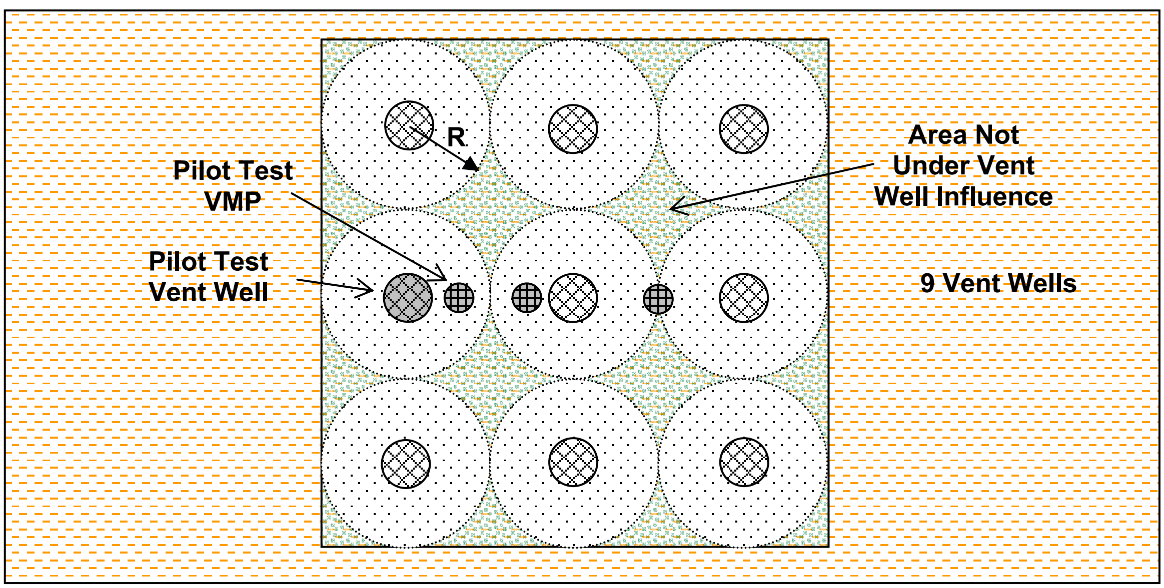

Figure 28. Vent wells spaced with in-line pattern.

The radius of influence (R) of each vent well can be determined by measuring subsurface gas pressure with distance from the vent well or, as done with passive bioventing, measuring subsurface oxygen concentrations. The radius of pressure influence is used to determine vent well spacing for conventional bioventing systems because using an electrically powered blower to inject air results in measurable increases in subsurface pressure that are related to increases in

subsurface oxygen levels (Leeson and Hinchee, 1997). With passive bioventing, the pressure difference between atmosphere and subsurface extends throughout the contaminated region and is independent of subsurface oxygen levels. Thus, the radius of oxygen influence is used to determine the spacing of vent wells for passive bioventing systems. The number and spacing of vent wells for the full-scale passive bioventing system is based on the radius of oxygen influence, rate of airflow, and oxygen utilization rate.

An initial estimate of the distance between vent wells should be based on the radius of oxygen influence (R) determined during the pilot test (see Section 4.5.2). For example, a 10-ft radius of oxygen influence means that 14 vent wells would be required if the offset pattern (Figure 27) were used to aerate a 60-ft by 60-ft area (3,600 sq ft) whereas nine wells would be needed if the inline pattern (Figure 28) were adopted. The wells spaced in the offset pattern would be expected to maintain subsurface oxygen at levels greater than 5% over more of the contaminated volume as compared to the inline pattern due to the greater number of vent wells. However, the spacing of vent wells should also account for the fact that as hydrocarbons are consumed, the oxygen utilization rate (k_0 as determined in Section 4.5.1) will decrease, which corresponds to increases in radius of oxygen influence.

The increase in the radius of oxygen influence due to decrease in oxygen utilization rate can be predicted according to:

$$R = \sqrt{\frac{Q_{in}(C_{in} - C_R)}{k_0 \pi H n_{air}}} \tag{4.1}$$

Figure 29 shows how the radius of oxygen influence increases as the oxygen utilization rate decreases for a given airflow rate based on Equation 4.1. At a site with an airflow rate of 0.2 cfm, the initial radius of oxygen influence of 10 ft with oxygen utilization rate of 5%/day may increase to approximately 30 feet once the utilization rate decreases to 0.5%/day as the hydrocarbons are degraded. The number of wells required to sustain oxygen above the 5% level would decrease from nine based in the initial 10 ft radius to one vent well with the 30-ft radius, assuming a 3,600 sq ft treatment area and an inline vent well layout. Thus, the vent well spacing should be a compromise between the initial estimate made when the oxygen utilization is greatest and the rate expected once the majority of hydrocarbons have been degraded.

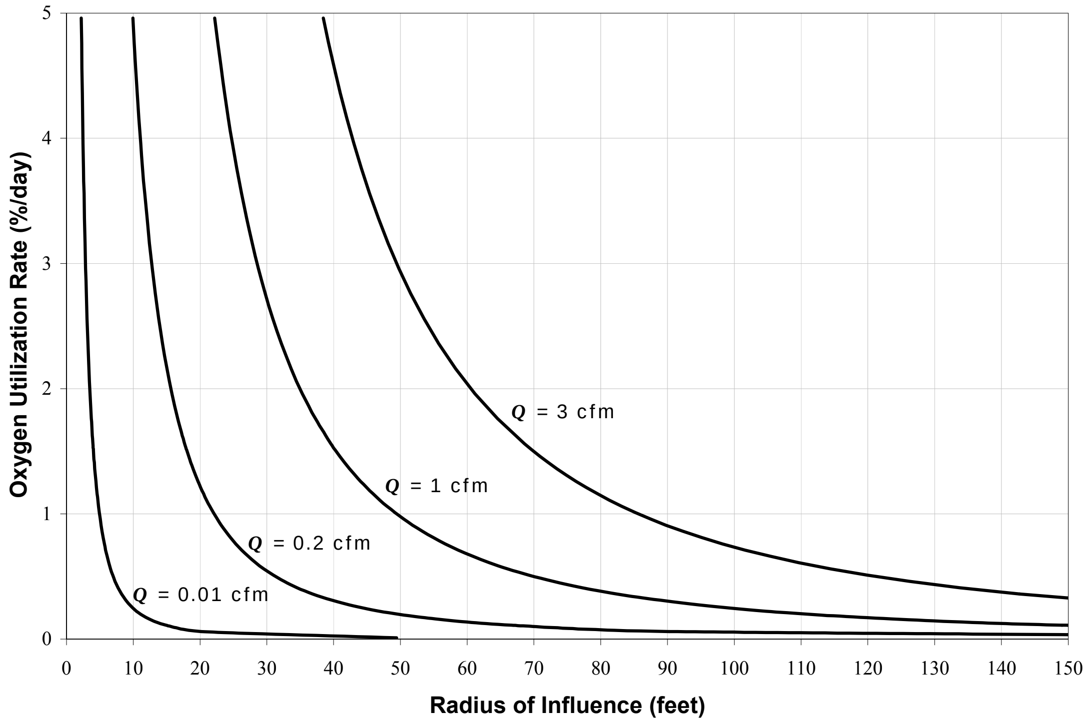

Figure 29. Radius of influence as a function of oxygen utilization rate and airflow rate. Assumes well screen length of 10 ft and air filled porosity of 0.3 (H = 10 ft, n = 0.3).

Well spacing should be determined by using the average airflow rate measured during the pilot-scale test and by assuming a reasonable oxygen utilization rate. For example, at a site with initial oxygen utilization rate of 5%/day with an airflow of 1 cfm, a well spacing of 100 ft (50-ft radius) might be appropriate assuming the oxygen utilization rate would decrease to 1% O_2/day once the hydrocarbons near the vent well were degraded. The radius of oxygen influence might be on the order of 20 ft immediately after installing the vent wells but is expected to grow out toward 50 ft over time.

5.2 PERFORMANCE MONITORING

Monitoring the performance of a passive bioventing system involves periodically retrieving and reviewing differential pressure and oxygen levels, which are measured at least hourly by automated sensors and recorded with a datalogger. Differential pressure is used to predict the rate of airflow using the pressure-airflow model (Section 4.5.3) where the rate of airflow can be used to estimate the volume of air delivered to the contaminated subsurface. Since maintaining oxygen levels at greater than 5% is the primary passive-bioventing performance objective, reviewing the long-term oxygen levels is the most important parameter to monitor for ensuring that the system will meet remedial goals.

5.2.1 Number of Measurement Locations

Differential pressure, the difference between the gas pressure in the sealed VMPs and barometric pressure, was described in Section 4.4.3 and diagrammed in Figure 23. Relative to measuring

airflow directly, differential pressure sensors are inexpensive, require less power, and are more durable for long-term monitoring of passive bioventing systems. Since passive bioventing is driven by the lag between changes in subsurface and barometric pressure, it follows that the pressure difference is relatively uniform throughout the subsurface. For example, the eight VMPs at the Castle Airport Pilot Test were found to yield essentially the same differential pressure response over a maximum separation of up to 32 ft (Figure 30). Therefore, few VMPs in addition to those installed during the pilot test will be required to characterize differential pressure at Castle Airport.

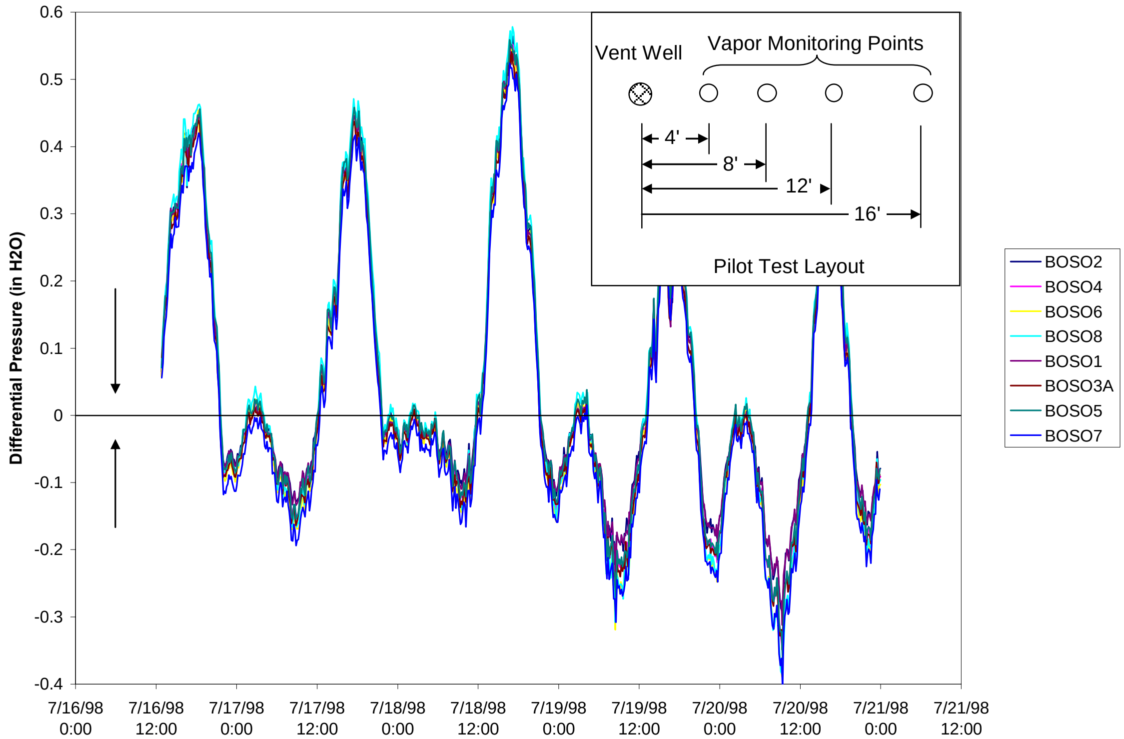

Figure 30. Differential pressure at eight VMPs from the Castle Airport passive bioventing demonstration.

In contrast to pressure, oxygen levels are expected to decrease with distance from each vent well, and more VMPs may be required in addition to those installed during the pilot test. The exact number of additional VMPs will depend on the performance monitoring goals. VMPs installed within the predicted radius of oxygen influence would be used to demonstrate that the vent wells are supplying adequate air to sustain oxygen levels greater than the 5% level. VMPs installed at or beyond the radius of oxygen influence would be used to evaluate the long-term performance in anticipation that oxygen levels would increase as hydrocarbons are degraded.

5.2.2 Measurement Frequency and Data Collection

How often automated sensor responses are recorded (i.e., measurement frequency) is a balance between collecting enough data to accurately represent the change in conditions versus the storage capacity of the datalogger. While there may be regulatory imposed data collection and evaluation schedules, the timing of data collection and retrieval is physically limited by the

datalogger storage capacity and battery life. Table 6 provides the stated maximum number of measurements that can be stored along with the battery life for three of the dataloggers that have been used during passive bioventing demonstrations. Also shown in Table 6 is an estimate for the number of days that eight sensor readings can be recorded per hour (192 readings/day) before the datalogger memory is filled. Sensor readings should be recorded on an hourly basis to capture atmospheric changes that occur throughout the day (Figure 30).

Table 6. Datalogger Storage Capacity and Battery Life

Datalogger	HOBO® H8 Onset Computer, Bourne, MA	Hermit 3000 In-Situ, Inc., Fort Collins, CO	CR23X Campbell Scientific, Inc., Logan, UT
Measurement capacity (bytes)	32,520	475,000	983,040
Estimated life (days) for eight sensors with hourly reading	174	2,474	5,120
Battery life (days)	365	730	40*
* Use solar recharger for extended data collection.			

The dataloggers should be retrieved at least yearly to evaluate system performance. However, more frequent data retrieval may be necessary due to limits of datalogger storage (e.g., HOBO H8) or battery life (e.g., CR23X).

5.2.3 Oxygen Utilization Rate and Soil Gas Hydrocarbons

The oxygen utilization rate is measured by closing the vent wells and measuring the decrease in VMP oxygen levels with time as described in Section 4.5.1. Determining the oxygen utilization rate on a periodic basis allows for the evaluation of changes in oxygen demand, which is expected to decrease over time indicating the degradation of hydrocarbons. Soil gas samples should be collected prior to the oxygen utilization test and analyzed to determine hydrocarbon concentrations. A decrease in utilization rate along with decrease in hydrocarbon soil gas concentrations would provide further evidence of remedial progress and could be used to justify collection of soil samples to quantify a change in hydrocarbon mass.

6.0 REFERENCES

Air Force Center for Environmental Excellence (AFCEE). 1996. *Bioventing Design Tool.* Available at http://www.afcee.brooks.af.mil/products/techtrans/bioventing/Biovresources.asp.

Apte, M.G., A.V. Nero, and K.L. Revzan, 1998. Meteorological Database for the United States. *Indoor Air*, 8:61-67. Available at http://eande.lbl.gov/IEP/high-radon/data/lbnl-met.html.

Baker, R. C., and C. Gimson, 2001. The effects of manufacturing methods on the precision of insertion and in-line thermal mass flowmeters. *Flow Measurement and Instrumentation,* 12(2):113-121.

Battelle, October 1995. *Passive Bioventing Driven by Natural Air Exchange at the Hill Air Force Base Site 280*. Prepared for Hill Air Force Base, UT.

Blond, A. N., and P. M. Downing, 1997. Rotating vanes vs. thermal anemometry technology. Technical Topic I003: Airflow Technical Products. Available at: http://www.airflow-usa.com/tech-topics/tech_topics_i003.asp.

Carslaw, H.S. and J.C. Yaeger, 1959. *Conduction of Heat in Solids*, 2nd Edition, Oxford University Pressure, Oxford, UK.

Christensen, A.G., H.H. Nielsen, and E.V. Fisher, 2003. *Passive Ventillation for Removing PCE from the Vadose Zone* (in Danish). Miljøprojekt Nr. 806, Teknologiudviklingsprogrammet for, jord- og grundvandsforurening. Available at http://www.mst.dk/udgiv/publikationer/2003/87-7972-612-7/html/default.htm.

Costanza, J. and J. Rossabi, June 2001. Natural Pressure-Driven Passive Bioventing. *In* Proceedings of the Fourth Tri-Service Environmental Technology Symposium..

Durst, F., S. Noppenberger, M. Still, and H. Venzke, 1996. Influence of humidity on hot-wire measurements. *Measurement Science and Technology,* 7:1517-1528.

Ellerd, M.G., J.W. Massmann, D.P. Schwaegler, and V.J. Rohay, 1999. Enhancements for Passive Vapor Extraction: The Hanford Study. *Ground Water,* 37(3):427-437.

Environmental Security Technology Certification Program (ESCTP), January 2004. *Cost and Performance Report, Natural Pressure-Driven Passive Bioventing.*

Environmental Security Technology Certification Program (ESCTP), November 2002. *Addendum, Natural Pressure-Driven Passive Bioventing.* Prepared for NFESC, Port Hueneme, CA.

Environmental Security Technology Certification Program (ESCTP). September 2000. *Natural Pressure-Driven Passive Bioventing*. Prepared for NFESC, Port Hueneme, CA.

FRTR, 2002. *Remediation Technologies Screening Matrix and Reference Guide* (4th ed.). Available at http://www.frtr.gov/matrix2/top_page.html.

Freeze, R.A. and J. A. Cherry, 1979. *Groundwater*. Prentice-Hall, Englewood Cliffs, NJ.

Hinchee, R.E. S.K. and Ong, 1992. A Rapid In Situ Respiration Test for Measuring Aerobic Biodegradation Rates of Hydrocarbons in Soil. *Journal Air Waste Management Association,* 42(10):1305-1312.

Hoeppel, R., T. Zwick, D. Foor, J. Kittel, R.E. Hinchee, F. Goetz, G. Watson, and L. Bowling, April 1995. *Application of Bioventing and Bioslurping Technologies at Naval Fuel Remediation Sites*. In Proceedings of the 21st Annual Environmental Symposium and Exhibition.

Johnston, R. and S. Fleeter, 1997. Compressible flow hot-wire calibration. *Experiments in Fluids* 22:444-446.

Leeson, A. and R.E. Hinchee, 1997. *Soil Bioventing: Principles and Practices.* Lewis Publishers, CRC Press, Inc. Boca Raton, FL.

Li, D.X. and P.D. Lundegard, 1996. Evaluation of Subsurface Oxygen Sensors for Remediation Monitoring. *Ground Water Monitoring and Remediation,* 16(1):106-111.

Massmann, J.W., 1989. Applying Groundwater Flow Models in Vapor Extraction System Deisgn. *Journal of Environmental Engineering,* 115(1):129-149.

Miller, R.N., D.C. Downey, V.A. Carmen, R.E. Hinchee, and A. Leeson, 1993. *A Summary of Bioventing Performance at Multiple Air Force Sites*. In Proceedings NGWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration.

National Research Council (NRC), 1993. *In Situ Bioremediation: When Does it Work?* National Academy Press, Washington, D.C.

Naval Facilities Engineering Service Center (NFESC), June 1996. *Bioventing Cost Estimator (BVCE) and User's Guide.* Technical Memorandum TM-2188-ENV.

Neeper, D.A., 2002. *Investigation of the vadose zone using barometric pressure cycles.* Journal of Contaminant Hydrology. 54(2002): 59-80.

Pirkle, R.J., D.E. Wyatt, V. Price, and B.B. Looney, 1992. *Barometric Pumping: The Connection Between the Vadose Zone and the Atmosphere*. The Focus Conference on Eastern Regional Ground Water Issues.

Riha, B.D., 2001. *Vadose Zone Remediation Assessment: M-Area Process Sewer Soil Vapor Extraction Units 782-5M, 782-7M, and 782-e.* WSRC-TR-2001-00077. Westinghouse Savannah River Company, Aiken, SC.

Rossabi, J. and R. Falta, 2002. Analytical Solution for Subsurface Gas Flow to a Well Induced by Surface Pressure Fluctuations. *Ground Water*, 40(1):67-75.

Rossabi, J., B.B. Looney, C.A. Eddy-Dilek, B. Riha, and V.J. Rohay, 1993. *Passive Remediation of Chlorinated Volatile Organic Compounds Using Barometric Pumping*. WSRC-MS-93-615, DOE. Westinghouse Savannah River Company, Aiken, SC.

Science Applications International Corporation (SAIC), May 2000. *Revised Final, Phase II RCRA Facility Investigation Report for Wright Army Airfield Bulk Fuel System (SWMU 35) at Fort Stewart, Georgia*. Prepared for the U.S. Army Corps of Engineers, Savannah District, under Contract No. DACA21-95-D-0022, Delivery Order No. 0023.

Stylianou, C., and B.A. DeVantier, 1995. Relative Air Permeability as Function of Saturation in Soil Venting. *Journal of Environmental Engineering*, 121(4): 337-347.

U.S. Army Corps of Engineers (USACE), June 2002. Engineering and Design: Soil Vapor Extraction and Bioventing Engineering Manual EM-1110-1-4001. Available at: http://www.environmental.usace.army.mil/info/technical/geotech/sve/sve.html.

U.S. Department of Agriculture, Natural Resources Conservation Service (USDA), 2003. National Soil Survey Handbook, title 430-VI, exhibit 618-9. Available: http://soils.usda.gov/technical/handbook/contents/part618p5a.html.

U.S. Environmental Protection Agency (USEPA) Office of Research and Development (ORD), September 1995. *Principles and Practices of Bioventing*. EPA/540/R-95/534.

U.S. Environmental Protection Agency (USEPA), October 1994. *Bioventing*. Chapter III In How to Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites: A Guide for Corrective Action Plan Reviewers. EPA 510-B-94-003 and EPA 510-B-95-007.

U.S. Geological Survey, June 2002. State Boundaries of the United States. In *National Atlas of the United States* available at http://nationalatlas.gov.

Zimmerman, C.T., B.M. Sass, T.C. Zwick, B.C. Alleman, C.A. Payne, R.E. Hoeppel, and L. Bowling, 1997. *Principles of Passive Aeration for Biodegradation of JP-5 Jet Fuel*. Bioventing Applications and Extensions. Battelle Press.

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APPENDIX A

DERIVATION OF AIRFLOW EQUATIONS

This appendix outlines the derivation of equations presented for estimating the pressure differential, the rate of airflow, and the radius of oxygen influence. The terms, values, units, and definitions used in the preceding sections are summarized in Table A.1.

Table A.1. Terms, Common Values, Units, and Definitions

Term	Value	Units	Definition
T	86,400	Sec	Barometric pressure period (24 hours)
P_{avg}	101,325	kg/m s^2 (Pascal)	Average atmospheric pressure
n_{air}	0.2	cm^3/cm^3	Air filled porosity
μ_{air}	1.83×10^{-5}	kg/m s	Viscosity of air at 18°C
r_w	0.0245	M	Radius of standard 2-in diameter well
t	21,600	sec	Peak barometric pressure after 6 hours

A.1 PRESSURE

Massmann (1989) derived the following equation to describe changes in subsurface pressure as a function of time and depth below ground surface:

$$\frac{\partial P_z}{\partial t} = \frac{k_{air}^z P_{avg}}{n_{air}\mu_{air}} \frac{\partial^2 P_z}{\partial z^2} \tag{A.1}$$

where P_z is air pressure within the subsurface, t is time, k_{air}^z is the effective vertical air-permeability, P_{avg} is the average atmospheric pressure, n_{air} is the air-filled porosity, μ_{air} is the air viscosity, and z is the depth below ground surface. The analytic solution for Equation A.1 is useful for estimating the pressure difference between the atmosphere and subsurface given a value for vertical air permeability. Assuming that the change in atmospheric pressure can be described as a periodic function:

$$P_{atm}(t) = \Delta P_{dirunal}^{\max} \sin\left(\frac{2\pi}{T}t\right) + P_{avg} \quad \text{at } z = 0 \tag{A.2}$$

where $\Delta P_{diurnal}^{\max}$ is the maximum pressure change that occurs each day from early morning to late afternoon, T is the period of pressure fluctuation (24 hours), t is time, and P_{avg} is the average atmospheric pressure (1 atm). The solution to Equation A.1 with the periodic pressure change described by Equation A.2 is given in Carslaw and Yaeger (1959), p.64 as:

$$P_z = \Delta P_{diurnal}^{\max} \exp\left(-z\sqrt{\frac{\pi}{TD_{eff}}}\right) \times \sin\left(\frac{2\pi}{T}t - z\sqrt{\frac{\pi}{TD_{eff}}}\right) + P_{avg} \tag{A.3}$$

The term $z\sqrt{\dfrac{\pi}{TD_{eff}}}$ is equal to $z\sqrt{\dfrac{\pi}{T}\dfrac{n_{air}\mu_{air}}{P_{avg}k_{air}^{z}}}$ after substituting the values for D_{eff} and represents both the pressure wave dampening factor and the amount the subsurface pressure change lags behind surface pressure change. The decay in wave amplitude and delay in subsurface pressure response are both inversely proportional to the vertical air permeability; thus, soils with low air permeability will dampen and delay the atmospheric pressure wave resulting in a pressure difference between the atmosphere and subsurface.

The difference between atmospheric and subsurface pressure (pressure differential) is found by subtracting Equation A.3 from A.2:

$$\Delta P_z = P_{atm} - P_z = \Delta P_{dirunal}^{\max}\sin\left(\frac{2\pi}{T}t\right) + P_{avg} - \left[\Delta P_{dirunal}^{\max}\exp\left(-z\sqrt{\frac{\pi}{TD_{eff}}}\right)\times\sin\left(\frac{2\pi}{T}t - z\sqrt{\frac{\pi}{TD_{eff}}}\right) + P_{avg}\right]$$

Eliminating P_{avg} and simplifying the expression yields:

$$\Delta P_z = \Delta P_{dirunal}^{\max}\left[\sin\left(\frac{2\pi}{T}t\right) - \exp\left(-z\sqrt{\frac{\pi}{TD_{eff}}}\right)\times\sin\left(\frac{2\pi}{T}t - z\sqrt{\frac{\pi}{TD_{eff}}}\right)\right] \qquad \text{(A.4)}$$

The pressure differential is evaluated at 6 hours, which represents the maximum change in diurnal pressure during the period of 24 hours:

$$\Delta P_z = \Delta P_{dirunal}^{\max}\left[\sin\left(\frac{2\pi}{24hrs}6hrs\right) - \exp\left(-z\sqrt{\frac{\pi}{TD_{eff}}}\right)\times\sin\left(\frac{2\pi}{24hrs}6hrs - z\sqrt{\frac{\pi}{TD_{eff}}}\right)\right]$$

Simplifying:

$$\Delta P_z = \Delta P_{dirunal}^{\max}\left[\sin\left(\frac{\pi}{2}\right) - \exp\left(-z\sqrt{\frac{\pi}{TD_{eff}}}\right)\times\sin\left(\frac{\pi}{2} - z\sqrt{\frac{\pi}{TD_{eff}}}\right)\right]$$

Substituting the value of $\sin\left(\dfrac{\pi}{2}\right)$, which is equal to 1, yields:

$$\Delta P_z = \Delta P_{dirunal}^{\max}\left[1 - \exp\left(-z\sqrt{\frac{\pi}{TD_{eff}}}\right)\times\sin\left(\frac{\pi}{2} - z\sqrt{\frac{\pi}{TD_{eff}}}\right)\right] \qquad \text{(A.5)}$$

The term $\dfrac{\pi}{TD_{eff}}$ is equal to $\dfrac{\pi}{T}\dfrac{n_{air}\mu_{air}}{P_{avg}k_{air}^{z}}$ after substituting the values for D_{eff} and can be simplified by substituting values for the air-filled porosity (n_{air} = 0.2 cm^3/cm^3), air viscosity ($\mu_{air} = 1.83\times10^{-5}$ kg/m s), P_{avg} (101,325 kg/m s^2), and converting permeability from units of m^2 to millidarcy:

$$\frac{\pi}{TDeff} = \frac{\pi}{86400\text{ s}}\left|\frac{\text{m s}^2}{101325\text{ kg}}\right|\frac{0.2\text{ cm}^3}{\text{cm}^3}\left|\frac{1.83\times10^{-5}\text{ kg}}{\text{m s}}\right|\frac{1.01\times10^{15}\text{ millidarcy}}{\text{m}^2}\left|\frac{\text{m}^2}{3.28^2\text{ ft}^2}\right| = 0.123\text{ millidarcy/ ft}^2$$

The simplified expression for estimating the pressure difference as a function of depth below ground surface in feet and vertical air permeability in millidarcy is:

$$\Delta P_z = \Delta P_{diurnal}^{\max}\left[1-\exp\left(-z\sqrt{\frac{0.123}{k_{air}^{z}}}\right)\times\sin\left(\frac{\pi}{2}-z\sqrt{\frac{0.123}{k_{air}^{z}}}\right)\right] \tag{A.6}$$

A.2 AIRFLOW FROM A VENT WELL

Rossabi and Falta (2002) derived the following equation for airflow in a vent well resulting from a step change in barometric pressure:

$$Q(t) = 2\pi b\frac{k_{air}^{radial}}{\mu_{air}}S_{wb}\frac{2}{\ln(2.25\alpha t)} \tag{A.7}$$

where S_{wb} is equal to ΔP_z in this document, b is the well screen length, and α is a time scaling factor. Rearranging Equation A.7 and substituting for S_{wb}:

$$Q(t) = b\frac{4\pi}{\mu_{air}}\frac{k_{air}^{radial}\Delta P_z}{\ln(2.25\alpha t)} \tag{A.8}$$

Equation A.8 can be simplified by substituting values for the well screen length (b = 10 ft), viscosity of air (μ_{air} = 1.83×10^{-5} kg/m s), and converting the permeability units from m^2 to millidarcy and the pressure units from Pascal (kg/m s^2) to psi:

10 ft	m	4π	m s	m^2	6,895 kg	35.315 ft^3	60 s	= 0.0303 /millidarcy psi
	3.28 ft		1.83×10^{-5} kg	1.01×10^{15} millidarcy	psi m s^2	m^3	min	

Equation A.8 becomes:

$$Q(t) = k_{air}^{radial}\Delta P_z\frac{0.0303}{\ln(2.25\alpha t)} \tag{A.9}$$

where the units for the radial air permeability are in millidarcy and the pressure differential (ΔP_z) units are psi. The term α is equal to:

$$\alpha = \frac{k_{air}^{radial}P_{avg}}{n_{air}\mu_{air}r_w^2} \tag{A.10}$$

and represents a damping factor that affects the rate of airflow. The larger the radial air permeability, the more quickly the rate of airflow diminishes with time. Substituting values for P_{avg} (101,325 kg/m s^2), the air-filled porosity (n_{air} = 0.2 cm^3/cm^3), air viscosity (μ_{air} = 1.83×10^{-5} kg/m s), and well radius (r_w = 0.0254 m for 2-in diameter well) into Equation A.10 and converting permeability from units of m^2 to millidarcy:

α =	101325 kg	cm^3	m s		m^2	= 0.0457/millidarcy s
	m s^2	0.2 cm^3	1.83×10^{-5} kg	(0.0245)^2 m^2	1.01×10^{15} millidarcy	

Substituting the value for α into Equation A.10 and evaluating the airflow 30 min (1,800 sec) after the step increase in pressure yields:

$$Q(t) = k_{air}^{radial} \Delta P_z \frac{0.0303}{\ln\left(2.25 \times 0.0457 \times 1080\,\text{sec} \times k_{air}^{radial}\right)} \text{ or } Q(t) = k_{air}^{radial} \Delta P_z \frac{0.0303}{\ln\left(49.32 \times k_{air}^{radial}\right)} \quad \text{(A.11)}$$

A.3 FLOW RATE TO SUSTAIN BIOVENTING

The volume of air within a cylindrical volume of soil around a vent well is approximately equal to:

$$V = \pi R^2 H n_{air} \quad \text{(A.12)}$$

where R is the radial distance from the well, H is the length of the well screen, and n_{air} soil air porosity (volume air/volume total). The approximate airflow rate required to replace the volume of air out to a radial distance R once every 12 hours is:

$$Q = \frac{V}{12\text{hr}} = \frac{\pi R^2 H n_{air}}{720\,\text{min}} \quad \text{(A.13)}$$

An alternative method of estimating the airflow rate required to sustain aerobic biodegradation is based on the oxygen utilization rate that has been described with a zero-order rate model according to:

$$\frac{dC}{dt} = -k_0 \quad \text{(A.14)}$$

where C is the concentration of oxygen in the subsurface soil, t is time, and k_0 is the zero-order rate coefficient. The change in oxygen distribution with time is described by the radial advection-dispersion reaction (ADR) equation:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial r^2} + \frac{D}{r}\frac{\partial C}{\partial r} - v\frac{\partial C}{\partial r} - k_0 \quad \text{(A.15)}$$

where D is the dispersion coefficient for oxygen, r is the radial distance from the vent well, and v is the velocity of air in the soil pores. Assuming that the concentration of oxygen is not changing with time and that the zero-order oxygen utilization rate accounts for oxygen dispersion, Equation A.15 simplifies to:

$$v\frac{dC}{dr} = -k_0 \quad \text{(A.16)}$$

Equation A.16 describes the balance between the steady-state distribution of oxygen and the oxygen utilization rate. The air velocity is not constant but depends on the distance from the vent well. The volumetric rate of airflow into the vent well is the same as the volumetric rate of airflow in soil near the well:

$$Q_{in} = v 2\pi r H n_{air} \text{ or } v = \frac{Q_{in}}{2\pi r H n_{air}}$$

Substituting into Equation A.16 yields:

$$\frac{Q_{in}}{2\pi r H n_{air}} \frac{dC}{dr} = -k_0 \tag{A.17}$$

Integrating Equation A.17 from the vent well screen (r_w) with oxygen concentration of C_{in} to the radial distance R with oxygen concentration C_R:

$$Q_{in} \int_{C_R}^{C_{in}} dC = -k_0 2\pi H n_{air} \int_R^{r_w} r dr$$

yields:

$$Q_{in}\left(C_{in} - C_R\right) = -k_0 2\pi H n_{air}\left(\frac{r_w^2}{2} - \frac{R^2}{2}\right)$$

that was rearranged to:

$$Q_{in} = \frac{k_0 2\pi H n_{air}}{C_{in} - C_R}\left(\frac{R^2}{2} - \frac{r_w^2}{2}\right) \tag{A.18}$$

Ignoring the $r_w^2/2$ term and substituting for the influent oxygen concentration of 21% for C_{in} and evaluating the airflow required to maintain oxygen at 5% at C_R ($C_{in} - C_R = 21 - 5 = 16$) leads to:

$$Q_{in} = \frac{k_0 \pi R^2 H n_{air}}{16} \text{ or } Q_{in} = \frac{k_0 V n_{air}}{16} \tag{A.19}$$

which describes the airflow rate required to maintain aerobic biodegradation in a subsurface volume (V). A conversion factor of 720 min/day is necessary since k_0 is often reported as % O_2/day while Q has unites of cubic feet per minute.

A.4 RADIUS OF INFLUENCE

Equation A.18 was rearranged to solve for R, the radius of oxygen influence:

$$R = \sqrt{\frac{Q_{in}(C_{in} - C_R)}{k_0 \pi H n_{air}} - r_w^2} \tag{A.20}$$

Ignoring the r_w^2 term leads to:

$$R = \sqrt{\frac{Q_{in}(C_{in} - C_R)}{k_0 \pi H n_{air}}}$$